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THESIS

APPLICATION OF THE WEIBULL DISTRIBUTION TO THE COST EFFECTIVENESS ANALYSIS SPREADSHEET MODEL (CEAMOD) FOR THE AIRCRAFT ENGINE COMPONENT IMPROVEMENT PROGRAM (CIP)

by

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December, 1994

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This thesis explores the application of the Weibull distribution to the Cost Effectiveness Analysis Spreadsheet Model (CEAMOD) for the Aircraft Engine Component Improvement Program (CIP). The current model assumes the exponential distribution for all unscheduled failures. This thesis explores whether the Weibull distribution can be used in the CEAMOD. This process is performed through the use of a simulation program and spreadsheet analysis. The thesis first examines past concerns that the use of the Weibull will create cyclic annual numbers of failures of a component over an engine's life. It then examines the empirical distributions of the number of failures per year generated from simulations for a range of Weibull parameters and compares these with the Poisson distribution resulting from the current CEAMOD assumption of exponential times between failures. Finally, it considers how life cycle costs considered by the CEAMOD will change if the Weibull distribution is assumed. The conclusion is that the nature of the distribution of the annual number of failures should be studied further before the Weibull is incorporated into the CEAMOD.

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I. INTRODUCTION

A. BACKGROUND

This thesis analyzes the input and methodology of the statistical distributions applied to the General Electric Aircraft Engines Cost Effectiveness Analysis Spreadsheet Model (GE CEAMOD).

The GE CEAMOD is a spreadsheet program, originally developed by Pratt and Whitney, and later refined by General Electric for use in analyzing the cost effectiveness of aircraft engine change proposals [Ref. 1]. The current release, Version 2.1, is written for use with the Microsoft EXCEL 4.0 program. Both the Navy and the Air Force use the CEAMOD program in conjunction with their prime contractors to determine whether an Engineering Change Proposal, as submitted by the manufacturer, is cost effective over the proposed life of the engine/component.

The CEAMOD program is used in support of the aircraft engine Component Improvement Program (CIP). The CIP has the following three objectives [Ref. 1]:

1. To maintain an engine design which allows the maximum aircraft availability at the lowest cost to the government.

2. To correct, as rapidly as possible, any design inadequacy which adversely affects safety of flight.

3. To correct any design inadequacy which causes unsatisfactory engine operation or adversely affects maintainability and logistic support in service.

The CEAMOD program supports the CIP by allowing engineers and program managers to analyze the expected life cycle costs differential between a current component and a proposed change in that component. Because the life of a component is typically many years, all future expected costs or savings are expressed in net present value terms. Since many of the factors included in the analysis are estimates, the final program output is subject to interpretation. In addition, there are other "softer" factors that are considered as well. These include: safety, increased mission effectiveness, and decreased overall downtime for maintenance and repairs. The CEAMOD does not analyze these factors, but none-the-less, they are critical to the overall decision of whether to incorporate the modification.

One factor that has been under discussion with the program developers and users is the assumption in CEAMOD of a constant component failure rate. By assuming that the failure rate of a component is constant, the time between failures can be described by the exponential probability distribution. There is a belief that assuming this distribution ensures the CEAMOD results, which show fairly constant numbers of failures per year, are representative of reality. However, the designers and users of CEAMOD have proposed that the Weibull distribution may reflect the reality of the times between component failures more accurately. The concern is that due to the Weibull's ability to reflect changing failure rates,

the CEAMOD program may become too complex [Ref. 9]. In addition, the question remaining to be investigated is: "can the Weibull be successfully introduced into the CEAMOD program without creating a cyclic nature to the number of component failures over time?"

B. OBJECTIVE

The objective of this thesis is to analyze one of the specific assumptions of the CEAMOD program. This assumption has to do with the current and proposed unscheduled failure rates for the component in question. The current program assumes that the time between failures of a component is distributed according to the exponential probability distribution. If the time between failures behaves according to the Weibull distribution, how are the number of failures per year affected? There are two relevant issues with regards to the objective, they are:

1. Can the number of failures per year be described by a simple probability distribution?
2. Are there any significant differences in the overall life-cycle costs for a component when the exponential distribution is replaced by the Weibull?

C. SCOPE

The scope of this thesis is limited to an analysis of a single component's change and how the use of the Weibull distribution instead of the exponential affects the expected

life cycle costs. This thesis will only focus on the expected costs of unscheduled maintenance (i.e. unexpected failures) and not on the costs associated with planned maintenance. The trial data used was provided by General Electric and was the example previously analyzed in Rau's thesis [Ref. 4].

D. METHODOLOGY

Due to the nature and limitations of the CEAMOD program, a simple substitution of the number of failures generated assuming the Weibull distribution was not possible [Ref. 9]. The exponential distribution provides for a constant failure rate. Thus, if a component reaches a certain point in its life where its failure rate is constant, it has no greater or lesser chance of failing in the next instant of time for any time during its life. The number of failures per year then has the Poisson probability distribution with the constant failure rate as its mean number per year. The Weibull distribution allows for a changing failure rate. The number of failures per year is no longer Poisson distributed. Thus, before the Weibull can be incorporated into the CEAMOD, the nature of the distribution of the number of failures per year must be understood.

To study the distribution of the number of failures per year, assuming Weibull times between failures, a simulation program was written in the SIMAN simulation language. A version of the CEAMOD was also developed to accept the SIMAN data so that a financial analysis of the effects from the

Weibull distribution could be conducted.

E. ORGANIZATION OF THE THESIS

Chapter II provides a background of the current CEAMOD program and analyzes its methodology and assumptions. Chapter III is an in depth explanation of the proposed changes and their expected effects on the program. Chapter IV describes the development of the SIMAN program and the financial spreadsheet. Chapter V is an analysis of the model output. Chapter VI contains a summary of the research efforts and its conclusions.

II. BACKGROUND OF THE CEA MODEL

A. DEVELOPMENT OF THE CURRENT MODEL

The GE CEAMOD program is an EXCEL-based spreadsheet program currently used by the Navy and Air Force to estimate the future costs of aircraft engine component modifications. This program was originally developed as a mainframe program by Pratt and Whitney at the request of the Air Force. General Electric later converted it to a PC based Lotus 1-2-3 spreadsheet and then to its current configuration as an EXCEL spreadsheet [Ref. 1].

The Navy and Air Force have adopted the current model as the primary analysis tool in determining whether a modification to an engine or group of engines is cost effective from a life-cycle point of view. As noted in the Reeves thesis [Ref. 1], the model does have its imperfections and "illogical" steps, but it is currently the most effective model to use in determining long term cost effectiveness. The CEAMOD Users Group meets twice a year to discuss and approve improvements to the model. Version 2.2 was approved at the meeting held on 29 November 1994.

B. ASSUMPTIONS OF THE CEAMOD PROGRAM

There are a number of assumptions that have been incorporated into the current CEAMOD program. The primary assumption is that it will incorporate only one hardware change at a time. The significance of this assumption is that

a proposed component modification is considered to be totally independent of any other component. Thus, one modification has no bearing on any other. Although this may be true in certain cases, it is not necessarily true in all cases. An aircraft engine is a complex assembly and the reliability of one component can and does have an impact on other components. This assumption was made primarily due to cost considerations in the development of the CEAMOD program.

The costs used in the model to calculate the Net Present value (NPV) are primarily maintenance and operational costs. Also included in the model are the "kit" costs and labor required to make the change. When a component modification is proposed and the data is analyzed using the CEAMOD, the expected life-cycle costs associated with the current configuration are compared to those of the proposed changes. Figure 2.1 is a chart outlining which costs are included and which are not.

Based upon these assumptions, the model is designed to ONLY include those logistics costs directly related to maintenance, operations and kit installation. All of the costs of developing the modification and program management are disregarded. For the most part it is a logical conclusion to not include the sunk costs of R&D and D&T, but if there is a significant life cycle cost differential between the current configuration and the proposed configuration for engineering data and program management these factors should be included.

COST CATEGORY	DESCRIPTION
COSTS INCLUDED IN MODEL	
Component Modification Cost	Cost to modify operational engines
Post-Modification Material Costs	Cost of materials for maintenance AFTER modification
Post-Modification Labor Costs	Cost of labor for maintenance AFTER modification
Technical Documentation Modification costs	Cost of re-writing and implementing new documentation
Post-Modification Support Equipment Costs	Cost of modifying or creating new support equipment
Post-Modification Inventory Costs	Cost of purchasing new inventory
Post-Modification Fuel Costs	Cost of change in fuel usage
Post-Modification Aircraft Loss Costs	Cost savings due to prevention of catastrophic aircraft loss
COSTS NOT INCLUDED IN MODEL	
Research and Development Costs	Cost to develop modification
Design and Test Costs	Funds spent to ensure that the component performs as designed
Engineering Data Costs	Cost to develop eng stds for new components
Program Management Costs	Administrative costs related to the program management

Table 2.1: CEAMOD cost inclusion/exclusion table

C. LIMITATIONS OF THE MODEL

Although the CEAMOD program is quite complex, there are some inherent limitations. One critical limitation is the spreadsheet's ability to incorporate only one component change at a time. This limitation is primarily due to the program's ability to accept only one failure rate. This may be overcome, at least partially, by combining several component changes into one "complex" change. This process of combining failure rates is unrelated to the use of the program, and must be calculated offline [Ref. 1]. Another possible way to address the problem is to incorporate one component at a time in successive runs of the model. The iterative process might be to shift the modified configuration data to the "current" column and the next modification to the "proposed" column. By doing this for all components, the overall cost of all modifications can be estimated. This process of incorporation must be handled with care, because the order of incorporation may affect the outcome. Some orderings may increase overall costs because of interactions with other parts of the engine.

Another limitation is related to the input data developed by the contractor/program manager. The data that is input into the program, both for costs and component reliability must be developed offline. Much of the data is estimated in the early stages of the program rather than being known precisely. Experience has shown that reality is different than the estimate. Thus, this program should not be used only at the inception of the program, but should be run at any time

there are significant changes to the relevant data. If the actual failure data of new components in service does not meet estimates, there may be a need to re-evaluate the modification policies. As a program develops, estimates of reliability and costs should be continually updated and entered into the program. Even small changes to reliability, cost or usage estimates may have a large effect on the total life cycle costs. These changes may lead the program manager to search for more reliable or cost-effective components.

A significant limitation of this program is the assumption of the exponential probability distribution for times between failures. It will be the focus of this thesis. The assumption of the exponential distribution results in expected failure rates being constant [Ref. 4]. The consequences of assuming the exponential distribution for times between failure is that the number of failures over a specified period of time is Poisson distributed with a mean which is the product of the failure rate and the specified length of time.

The input menu of the CEAMOD program requires a specific number to reflect the expected failure rate for both the current configuration and the proposed change. The rate is expressed as the expected number of failures per 1000 flight hours. The definition of "failure" is intentionally kept vague, and must be determined by the contractor/program manager. In the operating environment a failure may be defined as the time at which the component will no longer function, or

may be defined as the point at which it has failed to meet certain operating parameters.

The assumption of a constant failure rate has been a topic of discussion for several years by the CEAMOD Users Group. The reason is that the reality of component failures is that they tend to decrease as the "burn-in" period passes, stabilize during the majority of the expected life, and increase in the later "wear-out" period. This phenomenon can be illustrated by the well-known "bathtub curve" [Ref. 10]. Figure 2.2 is an example of a failure rate bathtub curve. In those periods of decreasing and increasing failure rates, the time between failures are best estimated by Weibull distribution [Ref. 5]. How to incorporate the Weibull assumption into the CEA model has been a question which the users' group has puzzled over for several years. The purpose of this thesis is to attempt to determine how to do that incorporation. The specifics of the Weibull distribution will be discussed in Chapter III.

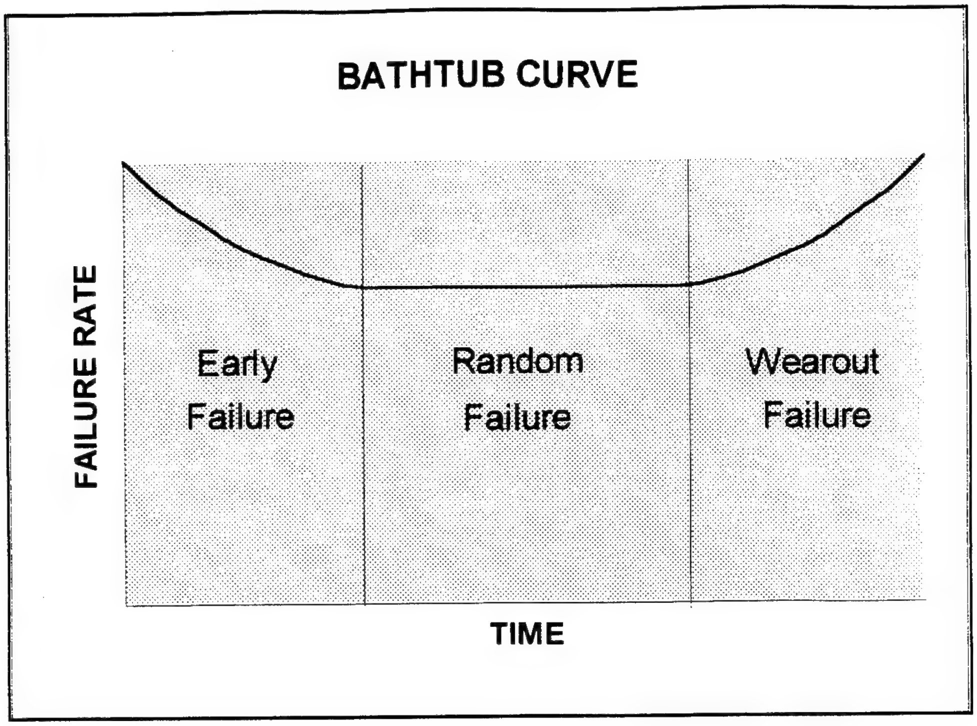


Figure 2.2: A failure rate bathtub curve

III. PROPOSED CHANGES

A. THE WEIBULL DISTRIBUTION

The Weibull Distribution is named after a Swedish Physicist named Waloddi Weibull, who in 1939, developed it to represent the breaking strength of materials [Ref. 5]. Since then it has become widely used in many areas of analysis, particularly those related to the modeling of reliability of electrical and mechanical components [Ref. 5]. The Weibull distribution most frequently provides the best fit for the type of failure data experienced in the gas turbine industry [Ref. 5]. Thus, the consideration of using the Weibull distribution for times between failures in the CEA model has been an issue for the last several years.

The probability density function (PDF), $f(t;\eta,\beta)$, of the Weibull distribution is represented by the following equation for values of $t\geq 0$, $\eta>0$, and $\beta>0$ [Ref. 8]:

$$f(t;\eta,\beta)=\frac{\beta}{\eta^{\beta}}t^{\beta-1}e^{-(\frac{t}{\eta})^{\beta}}. \tag{3.1}$$

The specifics of the Weibull distribution are explained below, preceded by definitions of its parameters:

1. Beta(β): Beta is commonly referred to as the "slope" parameter. The value of Beta ($\beta>0$) determines which member of the family of Weibull curves that best fits the data being analyzed. The type of failure may be any of those represented

by the bathtub curve. "Slopes" or β values less than one correspond to decreasing failure rates, typical of those found in the infant mortality segment of the bathtub curve, "slopes" or β values equal to one represent "random" failure where the failure rate is constant, and "slopes" or β values greater than one correspond to increasing failure rates, typical of those found in the wear-out segment of the bathtub curve. A Weibull distribution with a beta of one is the same as the exponential distribution.

2. Eta(η): Eta defines the "characteristic life" of the Weibull distribution. The characteristic life of a component, as represented by eta, represents the value at which 63.2% of all failures will occur regardless of the value of beta. The value of $1/\eta$ could be defined as the failure rate at the characteristic life in the Weibull distribution. The value of eta is the mean for the Weibull distribution (and, of course the exponential) when the value of beta is one, but is not the mean when the value of beta is less than or greater than one. Figure 3.2 shows graphically the shape of the PDF for several values of beta.

The hazard function describes the instantaneous failure rate. The hazard function for the Weibull distribution is represented by the following equation for value of $t \geq 0$, $\eta \geq 0$ and $\beta \geq 0$ [Ref. 8]:

$$h(t;\eta,\beta)=(\frac{1}{\eta})^{\beta}\beta t^{\beta-1}. \qquad (3.2)$$

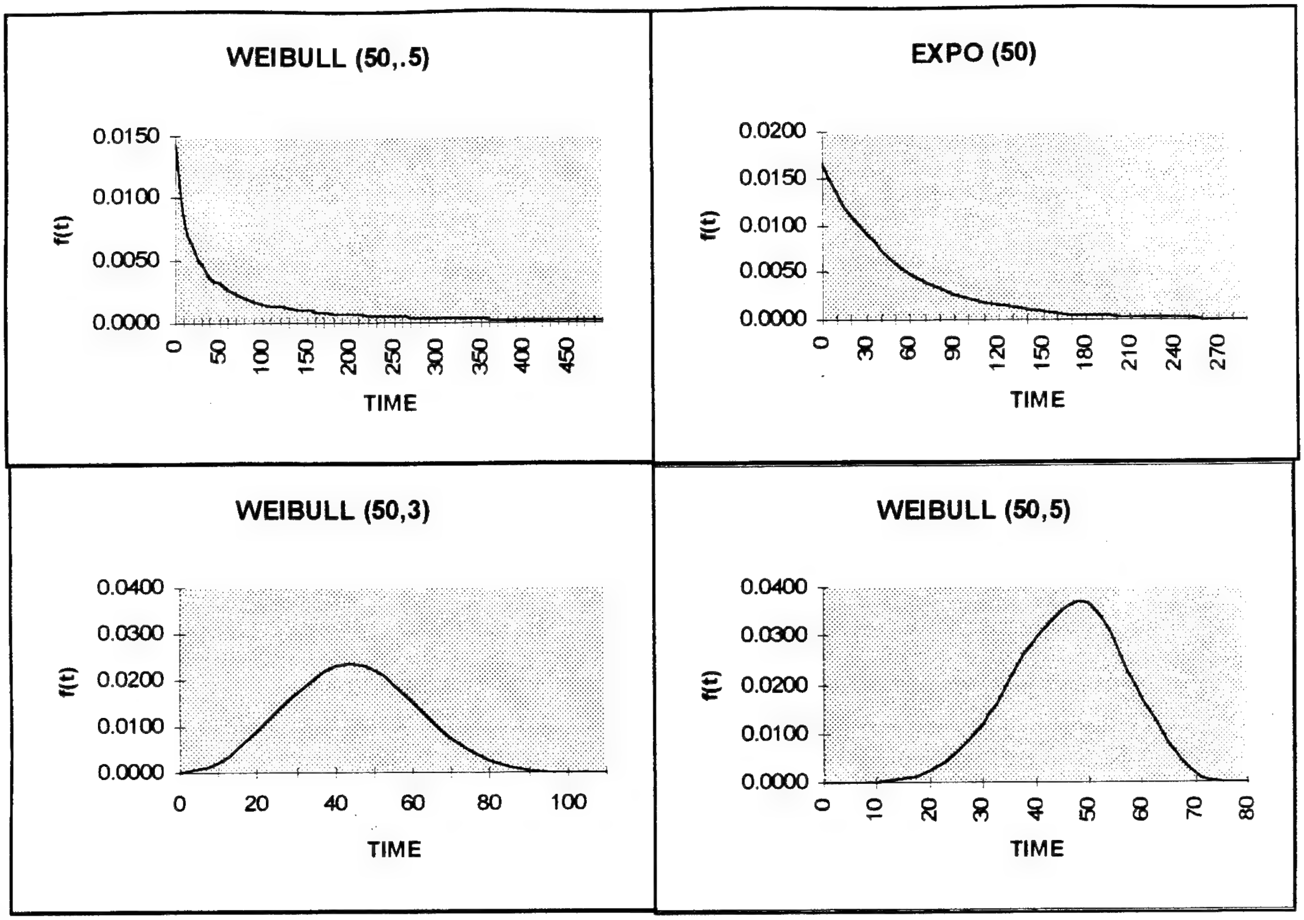


Figure 3.2: Weibull PDF curves

When $\beta = 1$ we have the exponential function, the hazard function becomes:

$$h(t;\eta,1)=\frac{1}{\eta}. \tag{3.3}$$

Thus, because the failure rate equals $1/\eta$, and η equals the mean for an exponential distribution, the hazard rate is simply defined as one over the mean.

The mean of the Weibull distribution for values of beta less than and greater than one is given by [Ref.7]:

$$\mu=(\frac{\eta}{\beta})\Gamma(\frac{1}{\beta}), \tag{3.4}$$

where $\Gamma(.)$ is the Gamma Function. The variance of the Weibull distribution is given by [Ref. 7]:

$$^{2}=(\frac{\eta^{2}}{\beta})(2\Gamma(\frac{2}{\beta})-\frac{1}{\beta}[\Gamma(\frac{1}{\beta})]^{2}). \tag{3.5}$$

A comparative example showing the mean and variance for different values of beta is provided in table 3.1:

β	η	t	h(t)	MTBF	^{2}
.5	50	50	.01	100	50000
1	50	50	.02	50	2500
2	50	50	.04	44.3	536.5

Table 3.1: Comparison of means and variances

Table 3.1 demonstrates that even though each example has the same η value (characteristic life) the actual mean values are very different. With a β = 1, or an exponential distribution, the mean is equal to the η value. But, when the beta value is less than one the mean is much higher and when the beta value is greater than one, the mean is less than the η value. The variance also decreases as the value of beta increases.

B. DETERMINATION OF WEIBULL PARAMETERS

In order to properly determine the Weibull distribution which fits a given set of failure data, the values of beta and eta need to be estimated. This process is called Weibull analysis [Ref. 5].

Weibull analysis is best performed using Weibull graph paper, an example of which is in Appendix A. In performing a Weibull analysis, there are several questions that need to be answered. The primary one being, "Can the data be described by the Weibull distribution?" A proper Weibull plot is represented by a straight line, thus if the data does create a straight or approximately straight line (where the majority of the points fall in a straight line, but there may be a few outliers), then the data can be represented by the Weibull distribution. Appendix A also contains a typical plot of Weibull data on Weibull graph paper.

Weibull graph paper has unique scales for the X and Y axes, which graphically will create a straight line if the data is Weibull. The values on the X axis represent the measure of life for the data, and are used as the primary estimator for the value of eta. The Y axis represents the expected cumulative percentage of components that have failed. By measuring from the 63.2% line on the Y axis, the value of beta can be determined.

Once time to failure data has been collected, it must be ordered from first failure to last failure. Once in the

proper order, the Median rank must be determined. Appendix B provides an example of a table for the determination of the median rank based upon the rank order and the sample size. Appendix B depicts the following (Sample size = 3):

Time to Failure	Median Rank
1 = 100 hrs	20.6
2 = 200 hrs	50.0
3 = 300 hrs	79.3

These values are plotted on the Weibull paper, with the hours on the X axis and the median rank on the Y axis. Next, a straight line is fitted to the data. Then eta is determined by drawing a vertical line down to the X axis from the point where the data line crosses the Y=63.2% horizontal line. This point on the X axis is the value of the characteristic life. In the case of the chart in Appendix A, that value is roughly 240 hours.

Beta is determined by moving down the data line to a point which is horizontally one inch away from the vertical line corresponding to the characteristic life and then measuring down from the intersection of the 63.2% line and the data line to the intersection of the horizontal and vertical lines. Slope is defined as rise over run, thus the distance in inches down to the "one-inch horizontal intersection" is the slope or the Beta value. In Appendix A the distance is 1.75 inches and therefore the value of Beta is 1.75. Because the value of Beta is greater than one, this indicates that the data is from a component which in the wearout stage of the

bathtub curve. Figure 3.5 depicts the probability density function of this data, with a $\beta = 1.75$ and an $\eta = 240$.

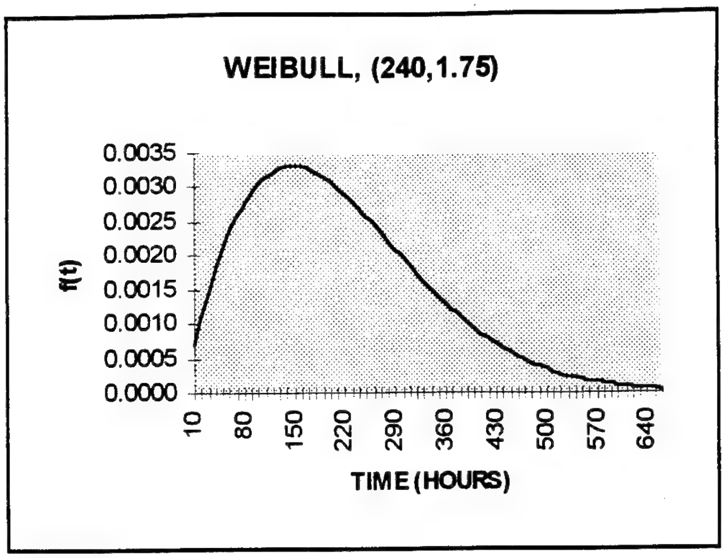


Figure 3.3: Weibull PDF for Appendix A example's parameters.

C. PROPOSED CHANGES TO THE CEAMOD PROGRAM

The proposal to incorporate the Weibull distribution into the CEAMOD program has been studied by General Electric and reference 9 states that they feel that Weibulls are too complex for this model. However, a Weibull distribution has the capability of allowing a failure rate that will change with time. For a given component in a system, the Weibull allows either an increasing, constant, or decreasing failure rate. In contrast, the exponential distribution assumes only that the failure rate is constant. Thus, if a component has reached a given number of operating hours, there is no greater

or lesser chance of failure after this point in time than at any other point in its life.

From an analytical point of view it is extremely difficult to incorporate Weibull generated failures into the CEAMOD program. The reason is that the distribution of failures over a given time interval is difficult to derive except in the case of $\beta = 1$. For that case the Poisson distribution can be used since times between failures are exponentially distributed. However, Professor James Esary of the Operations Research Department of the Naval Postgraduate School suggested that the use of simulation results should provide an empirical distribution which might be useful in the CEA model. Thus, this thesis uses a program to simulate what might happen if a component's times between failure were Weibull distributed.

This thesis will analyze simulations of a component's failures over a period of the expected life of an engine. To provide a basis for comparison, the general operating parameters for this component are assumed to be those provided by the General Electric example (a copy of the CEAMOD output for that example is presented in Appendix C). One intent of comparing the behavior of component failures represented by the exponential distribution to those represented by the Weibull distribution, is to determine whether there is a significant cost difference, in the long term, based upon the net present value of expenditures and savings.

IV. SIMULATION AND SPREADSHEET MODEL DEVELOPMENT

A. MODEL CONCEPT

The concept for the model is to simulate failures of a component over its expected life. The model incorporates failures that occur either in an exponential manner or in a Weibull manner over a period of ten years. As noted in the previous chapter by determining the time to failure and the annual number of failures, it should be possible to determine whether the use of the Weibull distribution is feasible.

B. SIMAN SIMULATION PROGRAM

In order to simulate this process, a simulation program, written in the SIMAN language was developed. Appendix D contains the program used to create the failure data.

The program begins by introducing ten engines into the system at time zero. It is assumed that all ten engines are in a "ready for flight" condition. The component of interest fails based upon the assumed distribution. The engine then enters into a repair facility, is repaired, and the engine is then again ready for service. That engine fails again at a future time based upon the assumed distribution, and the process is repeated.

In order to run this program, several assumptions were made. These are shown in Table 4.1. The basic time parameters were taken from the data provided by the General Electric example, and others were assumed by the author.

PARAMETER	VALUE	PROVIDED BY:
ANNUAL FLIGHT HRS	240	GE Example
MEAN TIMES TO FAIL (HOURS)	20,50,100,500	GE Example Author
REP FAC DELAY TIME (HOURS)	0	Author
NBR ENGINES/YEAR	10	Author
NBR OF REP FAC	1	Author
LIFE OF ENG (YRS)	10	Author

Table 4.1: SIMAN parameters for the failure event simulation.

The General Electric example uses an average annual fight hours value of 240 hours per aircraft per year. For the component being analyzed in the example, the assumption is that the current component has a MTBF of 50 hours and the proposed component has a MTBF of 500 hours. In addition to these values, MTBF values for the exponential distribution of 20 and 100 were chosen as well. The reason for these additional values was to simulate potential failures at a higher failure rate (20), and those at a rate (100) between the two values of the example problem. The benefit of this is to provide additional information for failure rate characteristics not necessarily in line with the original assumptions. The eta value (characteristic life) for the Weibull distribution was assigned using the same values as for the mean of the exponential distribution. The beta factors were all greater than one corresponding to a component having

an increasing failure rate. The beta values ranged from 1.5 to 5 (see Table 4.2).

The repair facility delay time of zero hours was a necessary assumption to ensure the SIMAN program was comparable with the CEAMOD in its assumptions of repair time. The number of engines introduced per year, ten, and the engine life value, ten years, were chosen to provide sufficient data points to complete a credible analysis. The number of repair facilities, one, has no impact on this simulation, but if a repair delay time was introduced it could impact the number of failures per year by being a potential bottleneck.

Once the parameter selection was made and the program written, the probability distribution of times between failures was assigned. As discussed above the author chose the following exponential and Weibull distributions to test in the program:

DISTRIBUTION	EXPO(MTBF), WEIBULL(η, β)
EXPONENTIAL	20,50,100,500 (hours)
WEIBULL	(20,1.5) (20,2) (20,3) (20,5)
WEIBULL	(50,1.5) (50,2) (50,3) (50,5)
WEIBULL	(100,1.5) (100,2) (100,3) (100,5)
WEIBULL	(500,1.5) (500,2) (500,3) (500,5)

Table 4.2: Distributions and their parameters used for failure times in the simulation (all times are expressed in hours).

As discussed in Chapter III, the actual means and variances for the Weibull are different than those for the exponential for the same eta value. Table 5.3 reflects the theoretical means and variances in hours for the assumed distributions presented in table 4.2. These values for the means and variances were computed using the equations (3.4) and (3.5) from Chapter III. The theoretical means, for any value of eta, tend to decrease as beta increases until it reaches approximately 2.2. At this point the mean begins to increase slowly, asymptotically approaching the mean of the exponential. The variances, for all values of eta, decrease as beta increases. Theoretically, for a beta value of infinity, the mean for the Weibull equals the mean for the exponential and the variance is zero.

The SIMAN program begins by creating ten "entities" (engines) and assigns consecutive engine numbers, "ENGNUMs", to each, beginning at one. The time of arrival into the program is assigned as the current time in the simulation. With the ten engines, all operationally capable, the program "delays" each engine by a time equivalent generated by the assumed distribution. This delay simulates the operational phase of each engine. At the end of the delay the engine component fails.

Once a failure has occurred, the engine enters into a repair queue to await repair. Once in repair the author assumes that the time in the repair facility is zero. Although this is not a realistic assumption for real world

operations, it was necessary to approximate the assumptions of the CEAMOD program. The CEAMOD assumes that each engine fails according to the exponential distribution, and does not assume that the repair channel may be a delaying factor in the return to operational capability. Thus the author has chosen a delay of zero for the repair channel. This SIMAN program can, of course, be easily modified to reflect the reality of repair channel delays.

After the repaired engine exits the repair channel, the time to failure is tallied for each engine. The engine is then returned to the point where the next delay time is generated. It is then delayed again by that amount and the process repeats.

Based upon the assumptions stated in Table 4.1, the program runs for a total of 2400 hours for each engine; that is, 240 hours per year for ten years. Because there is no "delay" for each engine in the repair channel, the "system" is in a steady state with no need for an initial warm-up period. If a delay time for repair were introduced, the SIMAN program would need to include some time for a warm-up in order to achieve steady state.

The data that was written to the tally files reflects the point in time when each failure occurred. An example output from the program is included in Appendix E. This output provides the program user with several important pieces of data. For each engine it lists the average time between failures (MTBF), the variation of the simulated times, the

Distribution	MTBF (Hours)	Variance (Hours)
Expo(20)	20.0	400.0
Weib(20,1.5)	18.1	150.3
Weib(20,2)	17.7	85.8
Weib(20,3)	17.9	42.1
Weib(20,5)	18.4	17.7
Expo(50)	50.0	2500.0
Weib(50,1.5)	45.1	939.2
Weib(50,2)	44.3	536.5
Weib(50,3)	44.6	263.3
Weib(50,5)	45.9	110.6
Expo(100)	100.0	10000.0
Weib(100,1.5)	90.3	3756.9
Weib(100,2)	88.6	2146.0
Weib(100,3)	89.3	1053.3
Weib(100,5)	91.4	442.3
Expo(500)	500.0	250000.0
Weib(500,1.5)	451.4	93922.6
Weib(500,2)	443.1	53650.5
Weib(500,3)	446.5	26333.2
Weib(500,5)	459.1	11057.5

Table 4.3: Theoretical means and variances for exponential and Weibull distributions.

minimum, maximum, and the total number of failures that could be expected over the life of 2400 hours.

The program also writes the actual failure times to "dat" files, as specified in the experimental frame. These "dat" files are important in analyzing the behavior of the failures, and the effect of the assumed statistical distribution. An example of the output from one file is included in Appendix F. The "dat" files can be converted to a spreadsheet readable format by using the "export" feature of SIMAN.

After importing the data into a spreadsheet, it can be easily analyzed and graphed to reflect the potential number of failures each year over the life of the engines. By reading the data from all ten engines into the spreadsheet, and grouping the number of failures by years (group together the failures from all engines, based upon the time of failure) it is easy to determine how many engines are expected to fail in any given year. These groupings can then be graphed to further visualize the number of failures each year over the life-cycle. Examples of such graphs are included in Appendix G.

The use of a simulation program is one way to generate a distribution of failures, and not necessarily the easiest way. By using a spreadsheet, such as Excel, a distribution can be created for the Weibull distribution. The benefit of this method is that it can be easily accomplished without the complication or expense of a simulation program. The drawback is that other parameters, such as a repair channel delay time

cannot be introduced.

The process for creating the Weibull failure times can be accomplished with the following equation:.

$$Weibull = \eta * (-\ln(rand))^{1/\beta}.$$

The value (-ln(rand)) is a spreadsheet command that takes the negative of the natural log of a randomly generated, uniformly distributed number between zero and one. By copying this equation down a column in the spreadsheet, an entire set of failures can be created. This equation creates a time to failure for each cell. Column D of table 4.4 is an example of the output from this process. In that table column E is then used to show the cumulative clock time. This is necessary to determine the cut-off point for failures over a specific period of time. Counting up the number of failures from Column D provides the number of failures over a given period of time. From Table 4.4 it is easy to see that during a period of 240 hours, there were seven failures. That is determined by simply counting the number of failures that occurred prior to the "cut-off" time of 240.

In order to analyze many engines over many years, the equation for generating failures can be copied to multiple columns, one for each engine. To determine the distribution of number of failures over all engines per year, the failure time columns can be analyzed using the "data analysis" function in Excel, and histograms representing number of

failures in a year can be plotted. This process is quite easy, and by changing the values of beta and eta, the distributions for all Weibull parameters can be determined.

A	B	C	D	E	F
1	BETA = 1		Failure	Cum Time	
2	ETA = 50		28.97	28.97	
3			19.77	48.74	
4			14.33	63.07	
5			9.76	72.83	
6			54.04	126.87	
7			32.16	159.03	
8			62.51	221.54	
9			58.78	280.32	

Table 4.4: Example of spreadsheet generated failure times.

In order to determine the potential effects of a given distribution, relative to the current CEAMOD program's assumptions, the data must be analyzed from a financial perspective. That is where a modified, simplified spreadsheet analysis comes into play. The next section will address this function.

C. EXCEL FINANCIAL SPREADSHEET PROGRAM

The financial spreadsheet developed by the author computes the net present value (NPV) of the proposed changes

over the life of the program. Appendix I contains examples of the spreadsheet program. The following are the specific assumptions and calculations included in the program.

1. ASSUMPTIONS AND CRITICAL VALUES (TOP LEFT CORNER OF SPREADSHEET)

a. Interest Rate (Row 1)

The assumed interest rate is 10% and is the discount rate at which the cost or savings from the modification will be valued for all future years. Thus a cost of $1000.00 next year is equivalent to $909.09 today. This is obtained by dividing the cost of $1000.00 by (1 + interest rate). For all future years, (1 + interest rate) is raised to the power of the number of years. Thus the value of $1000.00 in five years is equivalent to $1000/(1.10)^5$ or $620.92 today.

b. Flight Hours per Year (Row 2)

This value is defined as the expected number of flight hours each engine will operate for in each calendar year. Thus, for example, with ten engines operating, that value is multiplied by ten.

c. Cost of Modification (Row 3)

This cost is the expected cost of the modified component which is in excess of the current component's replacement cost. This value can be positive or negative depending upon the specific component. This value does not

include research and development costs. It is simply the difference between the cost of a new unit of the old component and the cost of a new unit of the new component.

d. Labor Cost (Row 4)

The cost per hour to have trained technicians replace the failed component. This price is an aggregate for all technicians needed to perform the job. This labor cost may be at either the organizational level, intermediate level, or depot level or all three. The assumption of $25.00 per hour is the organizational level labor rate.

e. Current Failure Rate (Row 5)

This rate is the expected number of failures per engine per flight hour. It is equivalent to one divided by the Mean Time Between Failures in flight hours for the exponential distribution. Therefore if the failure rate is .02 per flight hour then the MTBF is 50 flight hours. With 240 flight hours per year, the expected number of failures is (.02 * 240) or 4.8 failures per year assuming the exponential distribution for times between failures. The value displayed in Appendix I is the expected number of failures per flight hour, rounded to three significant digits.

f. Proposed Failure Rate (Row 6)

The proposed failure rate is defined in the same manner

as the current failure rate. It represents the failure rate of the proposed design change. This value is used to determine the total expected failures of the proposed configuration per year, and is rounded to three significant digits.

g. Labor Hours (Row 7)

This represents the number of hours of labor which will be required to repair an engine once it has failed. The labor hours multiplied by the Labor cost per hour represents the total cost (of labor) to repair each engine. For the example in Appendix I, ten is the assumed number of labor hours. This value could be incorporated into the SIMAN model as the repair channel delay time.

h. Current Failures per Year (Row 8)

This value represents the total number of expected failures per year per engine based upon the current configuration. This value is obtained from the output of the SIMAN program by taking the average number of failures for all engines over the ten-year period. If there are 1000 failures for ten engines in ten years, that equates to an average of ten failures per engine per year.

i. Projected Failures per Year (Row 9)

This value represents the total number of expected failures per year per engine based upon the proposed

configuration. This value is obtained from the output of the SIMAN program and is determined in the same manner as the current failures per year.

2. Spreadsheet Calculations

a. Year (Column 1)

This is the designation of the year in the life-cycle analysis: it begins at year one and continues through year twenty. Based upon the assumed engine life, an engine introduced in year one will be phased out of service ten years later, in year eleven.

b. Engines Introduced (Column 2)

This represents the number of engines with the improved component introduced in a given year. For sake of simplicity the author has chosen to introduce ten engines in each of the first ten years of the cycle. Each engine component is assumed to be introduced at the beginning of the year.

c. Attrition (Column 3)

This represents the number of engines or engines with specific components removed from service in a given year. The author has assumed a ten-year engine life and therefore the calculations show, for example, the engines being introduced in year one are being removed at the start of year eleven.

d. Total in Service (Column 4)

This represents the total number of engines operating during a given year. It is the sum of all previous introductions minus all previous attritions. All introductions and attritions are assumed to occur at the start of the year.

e. Total Flying Hours (Column 5)

This represents the expected total number of flying hours performed in a given year for all operational aircraft. This number is obtained by multiplying the expected number of flying hours per aircraft per year by the total number of engines in service during that year.

f. Current Expected Number of Failures (Column 6)

This represents the total number of failures that can be expected in a given year for the current configuration. This value is obtained by multiplying the total flying hours value by the current failure rate (row 8 of the assumption section). It may appear that the value in column 6 does not match this calculation because the value displayed for the current failure rate is only displayed to three significant digits. The actual value used is the complete value of the current failure rate (ten digits) without rounding.

g. Proposed Expected Number of Failures (Column 7)

This value represents the total number of failures that

can be expected in a given year for the proposed configuration. This value is obtained in the same manner as column 6 except that the "proposed" value (row 9 of the assumptions section) is used vice the "current" value (row 8 of the assumptions section).

h. Current Costs (Column 8)

This value represents the current year dollar value of expected outlays for maintenance of the current configuration due to failures. This figure is obtained by multiplying the Current Expected Failure values (column 6) by the labor cost and the labor hours value. In the first example in Appendix I, for year one, the current cost equals (120.7 failures x \$25 per hour x 10 hours) or \$30,175.00. The sum at the bottom of the column represents the total costs over the entire life cycle of operating an engine without a component modification.

i. Projected Costs (Column 9)

This value represents the current year dollar value of the expected outlays for maintenance due to failures of the proposed configuration. It is obtained by multiplying the number of engines introduced (column 2) by the cost of a modification, and adding that to the projected expected failures (column 7) multiplied by the product of labor cost and labor hours. The entry in the first example in Appendix I for year one equals

(10 new engines x \$1000 mod cost) + (47.2 expected failures x

$25.00 labor cost x 10 labor hours) which totals $21,800.00. The sum at the bottom of the column represents the total projected costs over the entire life cycle of operating an engine with a component modification.

j. Projected Savings (Column 10)

This value is the difference between the Current Costs and the Projected Costs (column 8 minus column 9). This value may be either positive or negative depending upon the overall cost differential. The sum at the bottom of this column represents the total savings over the entire life cycle of operating engines with the modification instead of without the modification.

k. NPV of Projected Savings (Column 11)

This value is the cumulative discounted value of the projected savings in each year. Since all costs are assumed to occur at the beginning of the year, the first year's value is not discounted. The present value of second year's cost represents the value of the projected savings for year two divided by $(1 + \text{interest rate})^{\text{year}-1}$, plus the savings from the previous year. In the first example in Appendix I, the savings for year three equals $(45,125/(1.1)^2$ +$32,693.00 = $69,986.57. The value at the bottom of the column represents the total net present value of the savings from making the configuration change. This is usually the key value of the CEA model. This value is used by the decision maker in

deciding whether it is worthwhile to make the change.

D. SUMMARY

By using the SIMAN program developed by the author, and the EXCEL spreadsheet program, it is possible to determine whether there can be any expected differences between the use of the Exponential and Weibull distributions.

The simulation of the life cycle of engine failures is critical to this analysis. By looking at the simulated failures of engines based upon an assumed distribution, it is possible to project the future. In an operational arena, through the use of Weibull analysis, the engineer would, with reasonable certainty, know what the failure distribution would be. By then using this distribution in a simulation program, he/she could see what would be expected in the long run.

The CEAMOD program has assumed that the distribution is exponential, even though the Weibull may be a more logical choice. Components of mechanical equipment do tend to wear out as time goes by. The Weibull allows the analyst to reasonably determine what is the expected life remaining of a component once it has operated for a given number of hours.

In the next chapter, the output data from the simulation program and the financial spreadsheet will be analyzed, and a comparison will be made considering the various parameter changes. For example, by comparing the expected number of failures from the exponential and the Weibull distributions, over the life cycle of the engines, it can be determined

whether there is any merit to changing to a Weibull-based analysis.

V. ANALYSIS OF OUTPUT

A. INTRODUCTION

This chapter will focus on the output provided by the SIMAN and financial spreadsheet programs. The purpose of this section is to compare the output data from the simulation using the CEAMOD assumption of an exponential distribution versus a Weibull distribution.

B. SIMAN PROGRAM OUTPUT

In order to produce the necessary output data for each of the relevant distributions (see Table 4.2), it was necessary to update the program after each run. The only change which needed to be made was to modify the "Delay" factor to reflect the distribution needed to produce the results.

The first analysis was to look at the simulated MTBFs of the components over the expected life of the engines. In order to determine the validity of the simulation model it was necessary to compare the SIMAN results to the theoretical means and variances. Table 5.1 provides that comparison. Based upon the comparison of the means and variances from a simulation of 100 engine years (ten engines for ten years each) to the means and variances of the theoretical distributions, it appears that the simulation replicated theory very closely. The highest difference between means occurred for Weib(500,2) but the simulated mean was only 5.7% lower than the theoretical mean. The highest variance

DIST	OBS MEAN	THEOR MEAN	DIFF (O-T)	OBS VAR	THEOR VAR	DIFF (O-T)
E(20)	19.8	20.0	(.2)	355.7	400	(44.3)
W(20,1.5)	18.0	18.1	.1	143.0	150.3	(7.3)
W(20,2)	17.7	17.7	0	82.7	85.8	(3.1)
W(20,3)	17.9	17.9	0	40.4	42.1	(1.7)
W(20,5)	18.4	18.4	0	16.6	17.7	(1.1)
E(50)	47.1	50.0	(2.9)	1964.4	2500	(535.6)
W(50,1.5)	45.5	45.1	.4	890.9	939.2	(48.3)
W(50,2)	44.3	44.3	0	521.6	536.5	(14.9)
W(50,3)	44.9	44.6	.3	259.8	263.3	(3.5)
W(50,5)	46.1	45.9	.2	108.3	110.6	(2.3)
E(100)	108.0	100.0	8	9967.3	10000	(32.7)
W(100,1.5)	95.3	90.3	5	3658.3	3756.9	(98)
W(100,2)	92.0	88.6	3.4	2056.3	2146.0	(89.7)
W(100,3)	91.6	89.3	2.3	1028.7	1053.3	(24.6)
W(100,5)	93.3	91.4	1.9	419.4	442.3	(22.9)
E(500)	517.2	500.0	17.2	155697	250000	(94303)
W(500,1.5)	437.0	451.4	(14.4)	71536.1	93922.6	(22386.5)
W(500,2)	419.1	443.1	(24)	43727.4	53650.5	(9923.1)
W(500,3)	447.8	446.5	1.3	22772.4	26333.2	(3560.8)
W(500,5)	458.8	459.1	(.3)	8588.0	11057.5	(2469.5)

Table 5.1: Comparison of observed to theoretical means and variances.

difference occurred for Expo(500) and the simulated variance was 60% lower than the theoretical variance. Both differences are mainly due to the fact that the mean times between failures are quite large and therefore longer simulation runs will be necessary before we could expect the simulated means and variances to converge to the theoretical values.

The second analysis undertaken was to determine whether the number of failures cycled over the years of the engine life cycle. The SIMAN program was run multiple times to simulate the potential number of times engines failed over each year. Appendix G provides a graphical illustration of the output from this process. Table 5.2 adds some additional information about the results.

As is graphically depicted in Appendix G, the "curve" of failures has the greatest "cyclic" nature when the exponential distribution is assumed. When the Weibull is used, even assuming the same characteristic life parameter, and the value of beta increases, the number of simulated failures in each year tends to smooth out.

This can best be interpreted by saying that for components that have been determined to be "wearout" candidates, and after a Weibull analysis has been conducted to determine the appropriate parameters for the Weibull distribution, the higher the beta value, the more likely it is that there will be a more constant number of failures per year. In the case of an assumption of a high characteristic life, 500 hours, the smoothing effect is less pronounced, but

DISTRIBUTION	AVG NBR OF COMPONENT FAILURES/YR	MAX NUMBER OF FAILURES IN ANY YEAR	MIN NUMBER OF FAILURES IN ANY YEAR
EXPO(20)	120.7	144	102
WEIB(20,1.5)	133.1	144	124
WEIB(20,2)	135.3	144	128
WEIB(20,3)	133.9	139	126
WEIB(20,5)	129.8	133	124
EXPO (50)	47.2	62	35
WEIB(50,1.5)	52.4	59	48
WEIB(50,2)	53.4	58	50
WEIB(50,3)	53.1	59	50
WEIB(50,5)	51.7	54	48
EXPO(100)	22.0	27	11
WEIB(100,1.5)	25.1	30	20
WEIB(100,2)	25.8	29	22
WEIB(100,3)	25.1	29	22
WEIB(100,5)	25.3	27	21
EXPO(500)	5.3	10	0
WEIB(500,1.5)	5.2	8	2
WEIB(500,2)	5.3	8	3
WEIB(500,3)	5.1	7	1
WEIB(500,5)	4.9	8	0

Table 5.2: Summary of simulated engine failures.

is still present. For components with a low MTBF (a high failure rate) the presence of the smoothing trend is quite pronounced.

From the data generated by the SIMAN simulation program, the author concludes that the Weibull distribution does not show an increase in the "cyclic" nature of the numbers of failure data, but, in fact shows a decrease in that phenomenon. The Weibull distribution for beta values greater than one appears to have a "smoothing" effect on the number of failures.

The third part of the analysis was to determine the nature of the distribution of the annual number of failures when the time between failures is Weibull distributed. Appendix H presents histograms which can be used to identify some characteristic distributions. The data for these plots was developed using the simulation program, and they represent the number of failures occurring each year for 100 engine years. The means and variances for each set of plots are summarized in Table 5.3. This table shows the mean number of failures per year for the Weibull decreases initially as the beta value increases. However it does begin to increase again once the beta value exceeds approximately 2.2. This phenomenon occurs for the same reason that the MTBF decreased until beta reached approximately 2.2 and then it increased as shown in Table 4.3. The variance of the number of failures, however, is a strongly decreasing function of beta.

This table also shows that the means and variances for

DISTRIBUTION	MEAN NBR OF FAILURES/YEAR	VARIANCE OF FAILURES/YEAR
EXPO(20)	12.07	10.22
WEIB(20,1.5)	13.31	5.02
WEIB(20,2)	13.53	2.87
WEIB(20,3)	13.39	1.83
WEIB(20,5)	12.98	.80
EXPO(50)	4.72	4.14
WEIB(50,1.5)	5.24	2.34
WEIB(50,2)	5.34	1.09
WEIB(50,3)	5.32	.94
WEIB(50,5)	5.17	.46
EXPO(100)	2.2	1.95
WEIB(100,1.5)	2.51	1.32
WEIB(100,2)	2.58	.83
WEIB(100,3)	2.51	.47
WEIB(100,5)	2.53	.29
EXPO (500)	.53	.49
WEIB(500,1.5)	.52	.35
WEIB(500,2)	.53	.31
WEIB(500,3)	.51	.25
WEIB(500,5)	.49	.27

Table 5.3: Mean number of failures per year and variance of number of failures per year.

the exponentially distributed failures are close in value but not equal. They are theoretically equal since the number of failures per year is Poisson. The slight differences here are consequences of a limited number of simulation runs.

On the first page in Appendix H, for those graphs with an eta value of 20, the exponential distribution represents an approximate Poisson distribution. In the case of each of the "Weibull plots" they do not look like a Poisson distribution or even a discrete form of a Normal distribution when beta is less than two. For beta values greater than two a Normal distribution using a continuity correction might be a reasonable approximation.

To better discern the nature of the transition from the Poisson for an eta of 20 and the approximate Normal for beta greater than two, two additional plots have been included on the second page of Appendix H. These plots have beta values of 1.25 and 1.75, and an eta value of 20. The mean number of failures per year for the Weibull(20,1.25) is 12.87 with a variance of 7.12. For the Weibull(20,1.75) the mean number of failures is 13.48 with a variance of 5.24.

The histograms for eta of 50, 100, and 500 are presented on the remainder of the pages in Appendix H and show an increasingly better Poisson distribution for the exponential failure times than was the case for the eta of 20. The transition to the Weibull and the influence of beta is also increasingly "smoother".

The fourth aspect of this analysis is to determine

whether the Weibull may have any impact on financial decision making. That will be addressed in the next section.

C. FINANCIAL SPREADSHEET ANALYSIS

One of the principal goals of the CIP program is to maintain an engine design which allows the maximum aircraft availability at the lowest cost to the government [Ref. 10]. Thus the question remains, "does the introduction of the Weibull distribution into the CEAMOD program more accurately the reflect the costs and/or potential savings?" By introducing the expected failure rates per year into the financial spreadsheet developed by the author, that question can be answered.

In order to most closely reflect the General Electric example, shown in Appendix C, the author has chosen to use the exponential MTBF of 50 as the base, and compare the other three values (20, 100, and 500) to that base. The only exception is the assumption that in making a comparison the designers would desire to move from a lower MTBF to a higher MTBF. Thus, in the comparison of 20 hours, that will be the "current" and 50 will be the "proposed". In the other two comparisons 50 is the "current" and either 100 or 500 is the "proposed".

The author has also chosen to first compare similar distributions. Thus the exponentials will be compared and the Weibulls with like beta values will only be compared. After that a comparison will be made between the exponential

and Weibull for unlike parameters. In that comparison exponential will be chosen as the "current" distribution and one of several Weibull distributions will be chosen for the "proposed".

The highlighted rows in Table 5.4 indicate the highest projected saving for each set of distribution comparisons. Example spreadsheets from which this data was extracted are provided in Appendix I. The savings for a Weibull distribution follow a similar pattern to the number of failures per year, increasing as beta increases to two, then slowly decreasing until they reach the level achieved by the exponential.

Based upon the projected costs/savings table, it is clear that given all assumptions previously discussed, there can be a significant savings differential between the projections based on both the exponential distribution and the Weibull. However, the savings between Weibulls is larger because the difference between the expected number of failures per year for the current configuration and the proposed configuration is larger with the Weibull assumption. Thus, one can expect a greater decrease in the number of failures per year with a Weibull assumption for both the current and proposed configurations. This greater decrease translates into an increase in potential savings. For example, the difference between the expected annual number of failures for Expo(20) and Expo(50) is 7.35 (12.07 for Expo(20) minus 4.72 for Expo(50)). For the comparison between Weib(20,1.5) and Weib(50,1.5) the difference is 8.07 (13.31 for Weib(20,1.5) minus 5.24 for Weib(50,1.5)).

CURRENT DISTRIBUTION	PROPOSED DISTRIBUTION	PROJECTED SAVINGS	FIRST YEAR OF POS CASH FLOW
EXPO (20)	EXPO (50)	$771,860	1
WEIB (20,1.5)	WEIB (50,1.5)	$854,092	1
WEIB (20,2)	**WEIB (50,2)**	**$867,797**	**1**
WEIB (20,3)	WEIB (50,3)	$854,092	1
WEIB (20,5)	WEIB (50,5)	$824,397	1
EXPO (50)	EXPO (100)	$220,221	3
WEIB (50,1.5)	WEIB(100,1.5)	$244,205	2
WEIB(50,2)	WEIB(100,2)	$247,632	2
WEIB(50,3)	**WEIB(100,3)**	**$253,342**	**2**
WEIB(50,5)	WEIB(100,5)	$233,926	3
EXPO(50)	EXPO(500)	$410,953	1
WEIB(50,1.5)	WEIB(500,1.5)	$471,485	1
WEIB(50,2)	**WEIB(500,2)**	**$481,764**	**1**
WEIB(50,3)	**WEIB(500,3)**	**$481,764**	**1**
WEIB(50,5)	WEIB(500,5)	$466,917	1

Table 5.4: Projected savings from changes in distribution parameters.

Table 5.5 provides a comparison of the projected costs/savings when changing from the exponential distribution to the Weibull. This might correspond to a situation where the old component had a constant failure rate and the new one did not. The values for the first two lines are negative because the comparison is between distributions with the same eta

CURRENT DISTRIBUTION	PROPOSED DISTRIBUTION	PROJECTED (COSTS)/SAVINGS
EXPO (20)	WEIB(20,1.5)	(209,211)
EXPO (20)	WEIB(20,5)	(171,522)
EXPO (20)	WEIB(50,1.5)	712,470
EXPO (20)	WEIB(50,2)	701,049
EXPO (50)	WEIB(100,1.5)	184,816

Table 5.5: Expected cost/savings comparison from changing from an exponential to a Weibull.

value. In these cases the average number of failures per year increases, thus there is an additional cost for this change. However, the cost is less for a WEIB(20,5) than for a WEIB(20,1.5) because the number of expected failures per year is less for the WEIB(20,5). For the next two lines, the comparison between an EXPO(20) and a WEIB(50,1.5) and WEIB(50,2) shows a savings, but not as great a savings as the change shown in Table 5.4 when the change was made with like distributions. This is due to the increase in the expected number of failures per year between distributions. The difference between the average number of failures for a comparison of EXPO(20) and EXPO(50) is 7.35. However, the difference between EXPO (20) and Weibull(50,1.5) is 6.83 and for Weibull(50,2) it is 6.73. This decrease in the difference between the current and proposed distributions accounts for the decrease in the projected savings. The savings are primarily achieved from the shift from an MTBF of 20 hours to one approaching 50 hours vice a shift to a different distribution. The same is true for the last comparison in

Table 5.5.

Based upon this analysis, the author concludes that there is a significant difference in costs between the exponential and Weibull distributions. In addition, when applied to Weibull with like beta values but differing eta values, those savings can be quite large. The savings for a Weibull distribution follow a similar pattern to the number of failures per year, increasing as beta increases to two, then slowly decreasing until they reach the level achieved by the exponential.

VI. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The key questions that needed to be answered by this thesis research effort were:

1. Does the assumption of the Weibull distribution mean that there will be "cyclic" numbers of failures over the years of the engine life-cycle?

2. What does the probability distribution for the number of failures in a year look like if failure times are Weibull?

3. Is there any significant difference in the net present value of future life cycle costs/savings by assuming the Weibull instead of the exponential distribution for the distribution of times between failures for an aircraft engine component?

The exponential is a special case of the Weibull and it is well known that if times between failures are exponentially distributed then the number of failures over a given period of time are Poisson distributed. However, for any other case of the Weibull the distribution of the number of failures over a given period of time cannot be derived analytically. Therefore, the use of simulation is needed to study the nature of this distribution. As a consequence, the author was able to generate the empirical distributions in question for a range of Weibull parameters. And, in addition, obtain an estimate of the mean number of component failures per year for different parameter values of the Weibull. That information

was then used in a simple version of the CEA model to compare the results derived from assuming exponentially distributed times between failures with the results from assuming Weibull distributed times between failures.

B. CONCLUSIONS

From the results of this analysis the three questions listed above can be answered. The answer to the first question regarding "cyclic" numbers of failures is that the use of the Weibull, with a shape factor greater than one, leads to less variation in the annual simulated number of failures than the exponential. As the beta value (shape factor) increases the variance in the total number of failures is reduced. However, the Weibull assumption with a shape factor greater than one does increase the expected number of failures per year since the mean time between failures becomes smaller.

With the data analyzed for this thesis, the distribution of the number of failures per year for the Weibull distribution appears to approximate the Normal distribution with beta values greater than two. When the beta value is one (the exponential distribution) the Poisson distribution is clearly represented and can be theoretically justified. With beta values between one and two, the distribution appears to be transitioning from Poisson to a Normal approximation. As the beta value increases the skewness of the distribution, and the variance decrease and it begins to approach an approximate

Normal distribution although this remains to be statistically tested.

The question regarding differences in the net present value of the life cycle costs of an aircraft engine under a proposed component change also produces a positive result. If, in fact, the component is failing in a manner that reflects a Weibull distribution and, there is a proposal to change a component to one that has a higher MTBF, the use of the Weibull may show a greater net present value of the savings than if the change was from assuming the component failed according to the exponential distribution. Based upon the analysis in this thesis those savings may be significant.

C. RECOMMENDATIONS

The author recommends that the use of the Weibull in the CEAMOD program continue to be evaluated. The first step in this process is to determine if a theoretical distribution can describe the number of failures per year. A Chi-square goodness of fit test of potential distributions should be made. Next, it is appropriate to determine what kinds of components actually do display the characteristics of the Weibull. One way is through Weibull analysis as shown in Appendix A. If a component has its time between failures described by a Weibull then incorporation into the model is justified, even if the number of failures distribution cannot be determined precisely.

In order to incorporate the Weibull into the CEAMOD, the

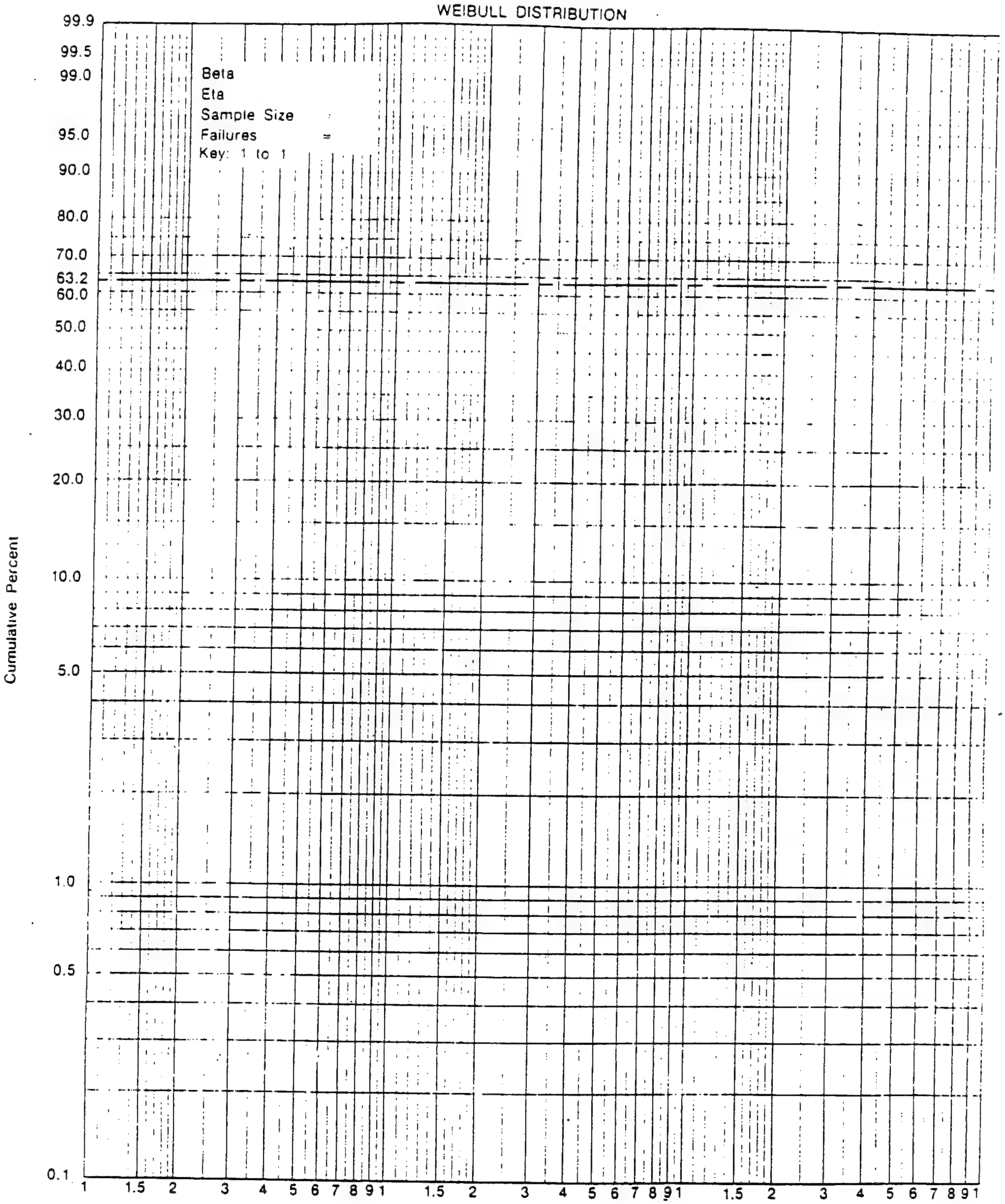
program designers will need to rewrite portions of the input and calculation sections of the model. A failure rate can not be used as an input value as is currently done for the exponential. The expected number of failures in a given time period will need to be the input value if the failures are Weibull. This can be estimated either by additional simulation runs, or by using a spreadsheet generated Weibull distribution with known beta and eta values (determined through Weibull analysis) as described in Chapter IV. Once this new input value has been determined, the calculations in the financial portion of the model can be modified to accommodate the new input data.

Finally, this thesis has also considered the variance of the exponential and Weibull distributions. It has shown that increased beta values (greater than one) result in reduced variance of the number of failures over a given period of time. This suggests that an analysis of the distribution of life cycle costs may be the next step in the evolution of the CEA model.

APPENDIX A: WEIBULL PAPER AND GRAPH

This first page of this appendix contains an example of blank Weibull graph paper taken from Reference 5. This paper is used to plot actual failure data to determine whether the data characteristics fit the Weibull distribution.

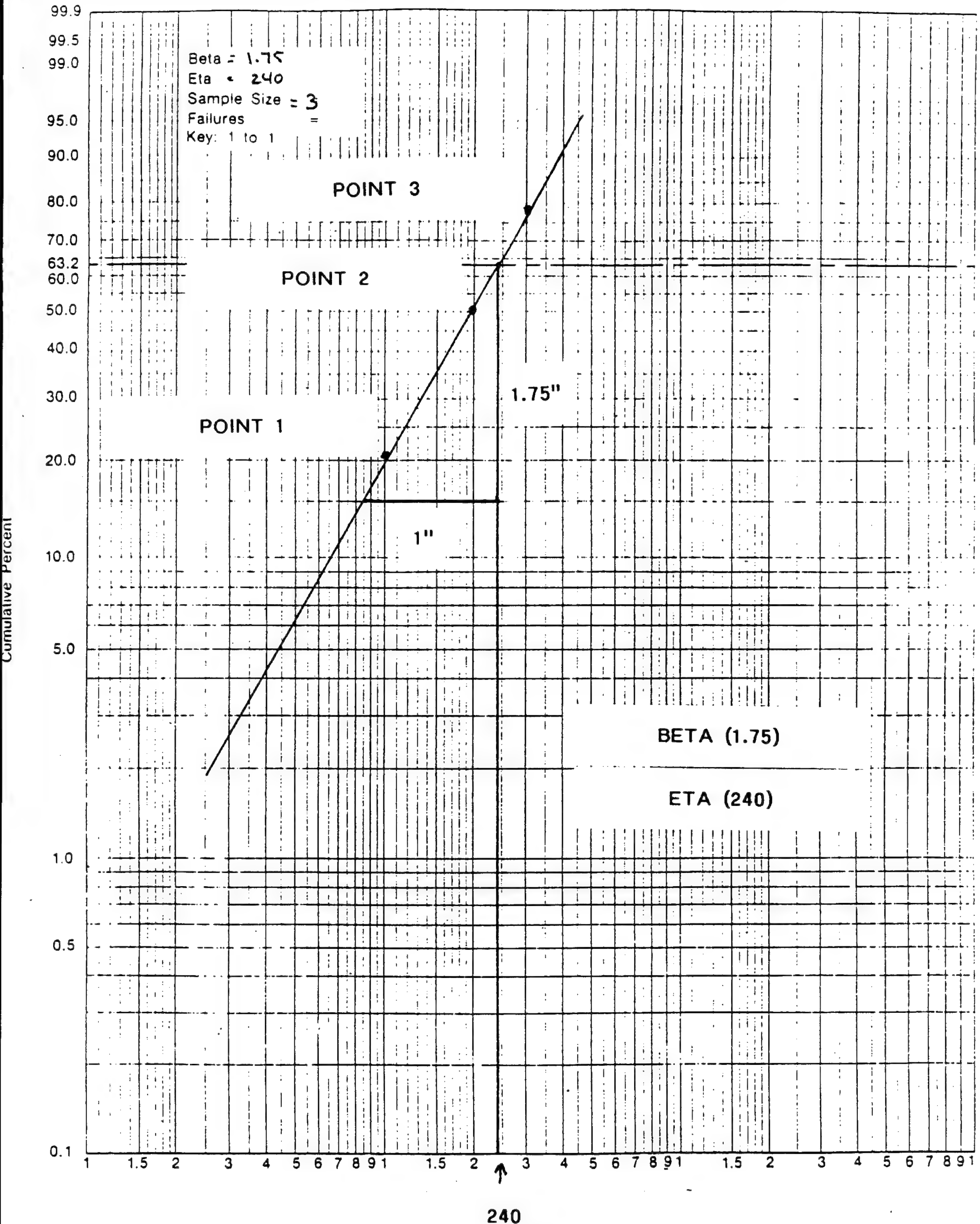
The second page contains a sample plot of three points, which is full explained in Chapter III.



WEIBULL DISTRIBUTION
Beta
Eta
Sample Size :
Failures =
Key: 1 to 1
Cumulative Percent
99.9
99.5
99.0
95.0
90.0
80.0
70.0
63.2
60.0
50.0
40.0
30.0
20.0
10.0
5.0
1.0
0.5
0.1
1 1.5 2 3 4 5 6 7 8 9 1 1.5 2 3 4 5 6 7 8 9 1 1.5 2 3 4 5 6 7 8 9 1

FD 265689

SAMPLE WEIBULL ANALYSIS



APPENDIX B:
MEDIAN RANK TABLE

MEDIAN RANK TABLE

RANK ORDER	1	2	3	4	5	6	7	8	9	10
1	50.0	29.2	20.6	15.9	12.9	10.9	9.4	8.3	7.4	6.6
2		70.7	50.0	38.5	31.3	26.4	22.8	20.1	17.9	16.2
3			79.3	61.4	50.0	42.1	36.4	32.0	28.6	25.8
4				84.0	68.6	58.8	50.0	44.0	39.3	35.5
5					87.0	73.5	63.5	55.9	50.0	45.1
6						89.0	77.1	67.9	60.6	54.8
7							90.5	79.8	71.3	64.4
8								91.7	82.0	74.1
9									92.5	83.7
10										93.3

RANK ORDER	11	12	13	14	15	16	17	18	19	20
1	6.1	5.6	5.1	4.8	4.5	4.2	3.9	3.7	3.5	3.4
2	14.7	13.5	12.5	11.7	10.9	10.2	9.6	9.1	8.6	8.2
3	23.5	21.6	20.0	18.6	17.4	16.3	15.4	14.5	13.6	13.1
4	32.3	29.7	27.5	25.6	23.9	22.4	21.1	20.0	18.9	18.0
5	41.1	37.8	35.0	32.5	30.4	28.5	26.9	25.4	24.1	22.9
6	50.0	45.9	42.5	39.5	36.9	37.4	32.7	30.9	29.3	27.8
7	58.8	54.0	50.0	46.5	43.4	40.8	38.4	36.3	34.4	32.7
8	67.6	62.1	57.4	53.4	50.0	46.9	44.2	41.8	39.6	37.7
9	76.4	70.2	64.9	60.4	56.5	53.0	50.0	47.2	44.8	42.6
10	85.2	78.3	72.4	67.4	63.0	59.1	55.7	52.7	50.0	47.5
11	93.8	86.4	79.9	74.3	69.5	65.2	61.5	58.1	55.1	52.4
12		94.3	87.4	81.3	76.0	71.4	67.2	63.6	60.3	57.3
13			94.8	88.2	82.5	77.5	73.0	69.0	65.5	62.2
14				95.1	89.0	83.6	78.8	74.5	70.6	67.2
15					95.4	89.7	84.5	79.9	75.8	72.1
16						95.7	90.3	85.4	81.0	77.0
17							96.0	90.8	86.1	81.9
18								96.2	91.3	86.8
19									96.4	91.7
20										96.5

The median rank table assigns the median value to each item in a sample size. The median rank is used for plotting against th X axis of Weibull graph paper. The highlighted value 3, is used as an example in Chapter III.

APPENDIX C: SAMPLE CEAMOD OUTPUT REPORT

This appendix contains the standard three page output report from the CEAMOD program. The input data is taken from Reference 4, and is the example data provided by General Electric.

TITLE
ENGINE MODEL Fwww-xx-yyy
TASK/ECP

F-zz

Standard Inputs	
Fiscal Year Dollars	1991
NPV Rate	10%
Labor Cost / Manhour at O&I	$32.32
Labor Cost / Manhour at Depot	$43.30
Cost to introduce new P/N - $ / PN	$1,524
Cost to Maintain each P/N / Year	$250
Fuel Cost / Gallon	$0.61
Test Fuel - Gallons / Hour	150
Flight Fuel - Gallons / Hour	150
EFH / Year	240
TAC / EFH Ratio	3.00
TOT / EFH Ratio	1.50
Aircraft Cost	$0

Task Incorporation Input

1.0	Incorporation Style. (1,2 or 3) 1 = Attrition 2 = Retrofit at 1st Opportunity 3 = Forced Retrofit		2
	Kits / Month	→	0
2.0	Does Kit Cost Replace Normal Maint. Material Cost? 1=Yes 0=No		0
3.0	Delta Production Cost		$10,000
4.0	Kit Hardware Cost - $ / Engine		$15,000
5.0	Kit Labor Manhours at O&I		2
6.0	Kit Labor Manhours at Depot		20
7.0	Technical Pubs Cost - Total $		$500
8.0	TCTO Cost - Total $		$1,500
9.0	Tooling/Support Equipment Cost-Total $		$500
10.0	Spare Parts Factor		0%
11.0	Scheduled % Events being Modified		100%
12.0	Unscheduled % Events being Modified		100%
13.0	Unscheduled Event Rate allowing Modification		0.020
14.0	Production Incorporation Date	Year →	1993	Month → 5
15.0	Field Incorporation Date	Year →	1993	Month → 8

		CURRENT	PROPOSED
	Scheduled Input		
16.0	Scheduled Maintenance Interval (TAC's)	3000	4000
17.0	Calculated Scheduled Maintenance Interval Rate/1000 EFH	1.000	0.750
18.0	Scheduled Manhours at O level	0.0	0.0
19.0	Scheduled % Removed at O&I level	100%	100%
20.0	Scheduled Manhours to Remove/Replace at O level	10.0	10.0
21.0	Scheduled Manhours at I level	25.0	25.0
22.0	Scheduled % at O&I requiring Repair	100%	100%
23.0	Scheduled Repair Cost at O&I level	$500	$500
24.0	Scheduled % Returned to Depot	100%	100%
25.0	Scheduled Manhours at Depot	10.0	10.0
26.0	Scheduled % at Depot requiring Repair	10%	1%
27.0	Scheduled Repair Cost at Depot	$25,000	$20,000
28.0	Scheduled % Scrapped	5%	1%
29.0	Hardware Cost to Scrap	$62,500	$50,000
30.0	Scheduled Engine Test Time	1.50	1.50
	Unscheduled Input		
31.0	Unscheduled Event Rate/1000 EFH	0.020	0.002
32.0	Unscheduled Manhours at O level	0.0	0.0
33.0	Unscheduled % Removed at O&I level	100%	100%
34.0	Unscheduled Manhours to Remove/Replace at O level	10.0	10.0
35.0	Unscheduled Manhours at I level	25.0	25.0
36.0	Unscheduled % at O&I requiring Repair	100%	100%
37.0	Unscheduled Repair cost at O&I level	$500	$500
38.0	Unscheduled % Returned to Depot	100%	100%
39.0	Unscheduled Manhours at Depot	10.0	10.0
40.0	Unscheduled % at Depot requiring Repair	3%	0%
41.0	Unscheduled Repair Cost at Depot	$1,250	$1,000
42.0	Unscheduled % Scrapped	1%	0%
43.0	Hardware Cost to Scrap	$62,500	$5,000
44.0	Unscheduled Engine Test Time	1.50	1.50
45.0	Unscheduled Secondary Damage Costs	$100,000	$100,000
46.0	Unscheduled Incidental Costs	$0	$0
47.0	Number of P/N's	4	4
	Optional Input		
48.0	% Improvement in Specific Fuel Consumption from Current to Proposed		0%
49.0	Aircraft Loss Rate Improvement / 1,000,000 EFH		0.00

CEA Guru

TITLE
ENGINE MODEL Fwww-xx-yyy F-zz
TASK/ECP

STANDARD HISTORY FILE

CEA VERSION 2 1

12/9/94

(N) Calendar Year	(O) No of Available Mod Months: Production	(P) Field	(Q) Engine Deliveries: Annual	(R) Cumulative	(S) Annual Engine Flight Hours: Fleet	(T) Average per Engine	(U) Cumulative Engines	(V) Attrition: Cumulative Whole Engine	(W) Annual Whole Engines
1993	8	5	0	0	0	240.00	0.00	0	0
1994	12	12	100	100	12,000	240.00	0.24	0	0
1995	12	12	125	225	38,880	240.00	1.02	1	1
1996	12	12	125	349	68,880	240.00	2.40	2	1
1997	12	12	150	498	101,520	240.00	4.43	4	2
1998	12	12	50	546	125,280	240.00	6.93	6	2
1999	12	12	0	544	130,800	240.00	9.55	9	3
2000	12	12	0	541	130,080	240.00	12.15	12	3
2001	12	12	0	538	129,360	240.00	14.74	14	2
2002	12	12	0	536	128,880	240.00	17.31	17	3
2003	12	12	0	533	128,160	240.00	19.88	19	2
2004	12	12	0	531	127,680	240.00	22.43	22	3
2005	12	12	0	528	126,960	240.00	24.97	24	2
2006	12	12	0	526	126,480	240.00	27.50	27	3
2007	12	12	0	523	125,760	240.00	30.01	30	3
2008	12	12	0	520	125,040	240.00	32.52	32	2
2009	12	12	0	518	124,560	240.00	35.01	35	3
2010	12	12	0	515	123,840	240.00	37.48	37	2
2011	12	12	0	513	123,360	240.00	39.95	39	2
2012	12	12	0	511	122,880	240.00	42.41	42	3
2013	12	12	0	508	122,160	240.00	44.85	44	2
2014	12	12	(91)	415	110,640	240.00	47.06	47	3
2015	12	12	(114)	298	85,440	240.00	48.77	48	1
2016	12	12	(114)	183	57,600	240.00	49.92	49	1
2017	12	12	(137)	45	27,360	240.00	50.47	50	1
2018	12	12	(91)	0	5,280	240.00	50.58	50	0
2019	12	12	(44)	0	0	240.00	50.58	50	0
2020	12	12	0	0	0	240.00	50.58	50	0
2021	12	12	0	0	0	240.00	50.58	50	0
2022	12	12	0	0	0	240.00	50.58	50	0
2023	12	12	0	0	0	240.00	50.58	50	0
2024	12	12	0	0	0	240.00	50.58	50	0
2025	12	12	0	0	0	240.00	50.58	50	0
Totals		Engines Delivered →	550	EFH →	2,528,880				50

EFH / Year = 240
TAC / EFH= 3.0
TOT / EFH= 1.5

Test Fuel - Gallons / Hour = 150
Flight Fuel - Gallons / Hour = 150
Aircraft Cost $0

Engine Attrition / EFH 0.00002

SUMMARY - Delta between current and proposed configurations
All values shown are THOUSANDS of fiscal year 1991 dollars.

		Cost	Savings
1)	Production Engine Cost	$5,500 K	
2)	Operational Engine Modification Cost		
3)	Follow-on Maintenance Material Cost		$17,633 K
4)	Follow-on Maintenance Labor Cost		$1,038 K
5)	Publications Cost	$2 K	
6)	Support Equipment Cost	$1 K	
7)	Part Number Cost	$6 K	
8)	Operational Fuel Cost		
9)	Aircraft Loss Cost		
	Totals	$5,509 K	$18,670 K
	Net Delta Dollar Impact		$13,162 K
	Net Present Value at 10%		$1,292 K

ASSUMPTIONS

a)	Incorporation in Production engines will begin in		May	1993
b)	Number of engines produced with this change is			550
c)	Number of spare units incorporating this change is			0
d)	Modification of operational engines can begin in		Aug	1993
e)	Incorporation of this change in operational engines will be accomplished by --->	1st Opportunity	at	Depot
f)	Total kits installed out of total engines not modified in production is	0	of	0
g)	Total engines lost to attrition is			50
h)	Total engines retired unmodified is			0
i)	Estimated yearly flying hours	240		EFH / Year

APPENDIX D: SIMAN SIMULATION PROGRAM

The first page of this appendix contains the SIMAN Model Frame for the simulation program used to generate the Weibull data. The process involved in the program is full explained in Chapter IV.

The second page contains the SIMAN Experimental Frame used in conjunction with the Model Frame to specify the specific parameters needed to run the program. The specifics of the experimental frame are fully explained in Chapter IV.

```
Begin,Yes,Yes;
;Model for the Simulation of a Weibull Distribution relative
;to the Aircraft Component Improvement Program
;
;           This is the Model portion of the SIMAN program.
;
;           Create Entity Module
            CREATE,10,0:,1;
;           Creates a distribution of failures of engine components
;           ten engines at time zero, max of one batch
            ASSIGN:X(1)=X(1)+1;
            ASSIGN:ENGNUM=X(1);
;           Assigns a sequential number 1 to 10 to each engine
Q1          ASSIGN: Arrtime=TNOW;
            DELAY:WEIB(50,5);
;           Delays each engine for the operating period, end of delay
;           is the failure.
            QUEUE,RepairQ;
            SEIZE:Repairman;
            DELAY: 0;
            RELEASE: Repairman;
;           These steps represent the repair process, delay of zero to
;           simulate assumptions of CEAMOD program
            TALLY:ENGNUM,INTERVAL(Arrtime);
;           This step collects the data on the time of failure
            DELAY:0:NEXT(Q1);
END;
```

```
BEGIN;
PROJECT, Thesis, Glenn R. Cook;
;
;              This is the experimental frame of the SIMAN program
;              it is designed to allow changes in the data for different
;              program runs.
;
ATTRIBUTES:    Arrtime:
               ENGNUM;
RESOURCES:     Repairman;
QUEUES:        RepairQ;
TALLIES:        1, Time for Engine 1, "Eng1.dat":
                2, Time for Engine 2, "Eng2.dat":
                3, Time for Engine 3, "Eng3.dat":
                4, Time for Engine 4, "Eng4.dat":
                5, Time for Engine 5, "Eng5.dat":
                6, Time for Engine 6, "Eng6.dat":
                7, Time for Engine 7, "Eng7.dat":
                8, Time for Engine 8, "Eng8.dat":
                9, Time for Engine 9, "Eng9.dat":
               10, Time for Engine 10, "Eng10.dat";
               REPLICATE, 10,0,240,N,Y,0;
;              This indicates that the program will run once for 2400
;              units of time.
END;
```

APPENDIX E: SIMAN OUTPUT REPORTS

This appendix contains the output reports generated by the SIMAN program. The author has chosen to only include examples from the simulation runs, thus this appendix only has the reports from the runs with an eta value of 20. The reports are fully explained in Chapter IV.

SIMAN IV - License #9050352
Naval Post-Graduate School

EXPO (20)

Project: Thesis
Analyst: Glenn R.Cook

Run execution date : 11/27/1994
Model revision date: 11/27/1994

Replication ended at time : 2400.0

TALLY VARIABLES

Identifier	Average	Variation	Minimum	Maximum	Observations
Time for Engine 1	19.351	.94969	.20862	83.182	122
Time for Engine 2	17.520	.94349	.35883	73.424	135
Time for Engine 3	19.741	1.0464	.12021	103.66	121
Time for Engine 4	21.066	.95621	.17511	109.84	113
Time for Engine 5	19.186	.92286	.09282	96.620	125
Time for Engine 6	19.296	.83613	.34302	84.389	124
Time for Engine 7	20.700	.95878	.27664	116.35	115
Time for Engine 8	20.483	1.0106	1.1141	113.80	116
Time for Engine 9	18.795	.89282	.10558	90.237	127
Time for Engine 10	21.799	1.0095	.07690	108.14	109

Run Time: 0 min(s) 2 sec(s)
Simulation run complete.

Mean = 19.79 Hours
Variance = 355.7 Hours
Fail/Eng/Year = 12.07

SIMAN IV - License #9050352
Naval Post-Graduate School

Weibull(20,1.5)

Project: Thesis
Analyst: Glenn R.Cook

Run execution date : 11/27/1994
Model revision date: 11/27/1994

Replication ended at time : 2400.0

TALLY VARIABLES

Identifier	Average	Variation	Minimum	Maximum	Observations
Time for Engine 1	17.710	.64641	1.2111	52.406	135
Time for Engine 2	17.271	.69992	.55646	62.322	138
Time for Engine 3	16.077	.65722	.29150	53.101	149
Time for Engine 4	19.058	.60095	1.4608	58.326	125
Time for Engine 5	16.727	.64935	1.3782	51.809	143
Time for Engine 6	19.110	.66742	1.4340	64.694	125
Time for Engine 7	19.280	.71869	.85501	63.743	121
Time for Engine 8	17.493	.67730	.59326	55.313	137
Time for Engine 9	19.460	.64598	1.1069	59.900	122
Time for Engine 10	17.619	.69236	.84961	69.638	136

Run Time: 0 min(s) 3 sec(s)
Simulation run complete.

Mean = 17.98 Hours
Varaince = 143.0 Hours
Fail/Eng/Year = 13.31

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Naval Post-Graduate School

Weibull (20,2)

Project: Thesis
Analyst: Glenn R.Cook

Run execution date : 11/27/1994
Model revision date: 11/27/1994

Replication ended at time : 2400.0

TALLY VARIABLES

Identifier	Average	Variation	Minimum	Maximum	Observations
Time for Engine 1	18.233	.52208	1.4531	50.979	131
Time for Engine 2	17.019	.54696	1.4297	41.855	141
Time for Engine 3	18.124	.48846	3.5033	39.402	132
Time for Engine 4	17.884	.54376	1.2400	51.982	133
Time for Engine 5	17.613	.52332	2.0428	46.506	135
Time for Engine 6	16.724	.49560	2.3522	42.024	143
Time for Engine 7	17.715	.48766	2.9432	45.533	135
Time for Engine 8	18.128	.49125	2.7711	42.892	132
Time for Engine 9	17.708	.54230	.83887	48.240	134
Time for Engine 10	17.488	.50650	1.3625	45.068	137

Run Time: 0 min(s) 2 sec(s)
Simulation run complete.

Mean = 17.66 Hours
Variance = 82.7 Hours
Fail/Eng/Year = 13.53

SIMAN IV - License #9050352
Naval Post-Graduate School

Weibull (20,3)

Project: Thesis
Analyst: Glenn R.Cook

Run execution date : 11/27/1994
Model revision date: 11/27/1994

Replication ended at time : 2400.0

TALLY VARIABLES

Identifier	Average	Variation	Minimum	Maximum	Observations
Time for Engine 1	18.885	.35075	2.4143	33.810	127
Time for Engine 2	17.435	.37529	3.3360	35.705	137
Time for Engine 3	17.560	.33070	5.2358	33.048	136
Time for Engine 4	17.641	.38849	4.1221	37.807	136
Time for Engine 5	17.803	.33332	6.5280	33.660	134
Time for Engine 6	17.500	.37213	3.1330	37.320	136
Time for Engine 7	18.031	.37175	3.4824	32.318	133
Time for Engine 8	18.094	.36543	5.6019	35.971	132
Time for Engine 9	17.681	.33839	4.8010	29.547	135
Time for Engine 10	17.921	.33384	4.1352	35.286	133

Run Time: 0 min(s) 3 sec(s)
Simulation run complete.

Mean = 17.85 Hours
Varaince = 40.4 Hours
Fail/Eng/Year = 13.39

SIMAN IV - License #9050352
Naval Post-Graduate School

Weibull (20,5)

Project: Thesis
Analyst: Glenn R.Cook

Run execution date : 11/27/1994
Model revision date: 11/27/1994

Replication ended at time : 2400.0

TALLY VARIABLES

Identifier	Average	Variation	Minimum	Maximum	Observations
Time for Engine 1	18.216	.21669	9.0715	27.425	131
Time for Engine 2	18.339	.26445	6.9617	29.079	130
Time for Engine 3	18.397	.23844	7.1913	27.333	130
Time for Engine 4	18.336	.20049	10.339	26.597	130
Time for Engine 5	18.592	.20915	6.5764	27.137	128
Time for Engine 6	18.693	.21916	8.6234	28.126	128
Time for Engine 7	18.137	.22710	6.8289	27.794	132
Time for Engine 8	18.587	.21210	9.3200	27.573	129
Time for Engine 9	18.436	.20319	7.7681	27.680	130
Time for Engine 10	18.332	.22248	7.7532	28.317	130

Run Time: 0 min(s) 3 sec(s)
Simulation run complete.

Mean = 18.41 Hours
Variance = 16.6 Hours
Fail/Eng/Year = 12.98

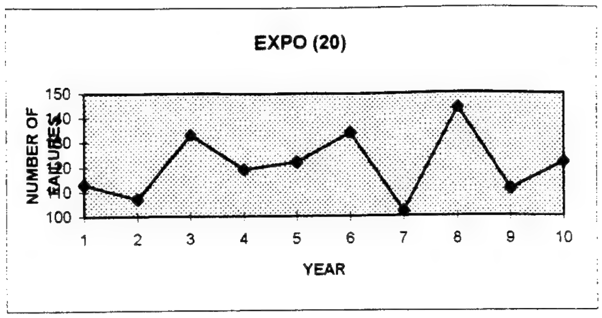
APPENDIX F: SIMAN "DAT" FILE OUTPUT

This appendix contains the output of a SIMAN "Dat" file. The first column is the cumulative clock time from the first failure to the total run of 2400 hours. The second column represents the actual times to failure for engine 1. The use of this data is fully explained in Chapter IV.

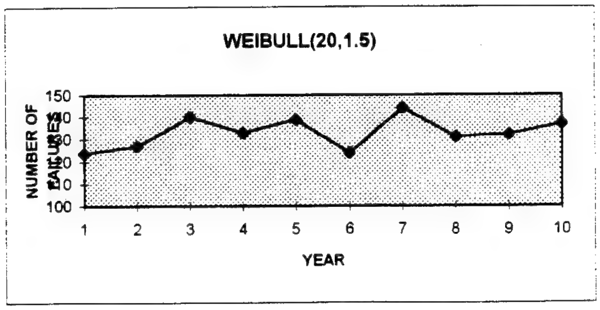
```
Time for Engine 1
 .13679400E+03   .13679400E+03
 .16538160E+03   .28587570E+02
 .30977810E+03   .14439650E+03
 .43940080E+03   .12962270E+03
 .55595120E+03   .11655040E+03
 .62420570E+03   .68254580E+02
 .64869380E+03   .24488100E+02
 .66302080E+03   .14326970E+02
 .69013670E+03   .27115910E+02
 .82652700E+03   .13639030E+03
 .86262820E+03   .36101140E+02
 .96482040E+03   .10219230E+03
 .97945980E+03   .14639340E+02
 .10163370E+04   .36877080E+02
 .11069960E+04   .90659120E+02
 .12023170E+04   .95320680E+02
 .15486620E+04   .34634510E+03
 .16954530E+04   .14679170E+03
 .17580750E+04   .62621460E+02
 .19088880E+04   .15081300E+03
 .21682330E+04   .25934500E+03
 .22424920E+04   .74259520E+02
 .23284450E+04   .85952880E+02
-.10000000E+01 -.10000000E+01
```

APPENDIX G:
GRAPHS OF ANNUAL NUMBER OF FAILURES

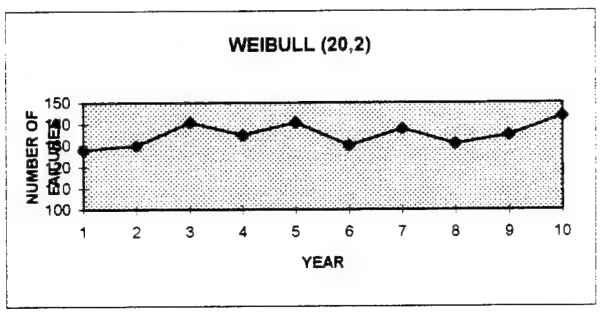
Year	Frequency
1	113
2	107
3	133
4	119
5	122
6	134
7	102
8	144
9	111
10	122
More	0



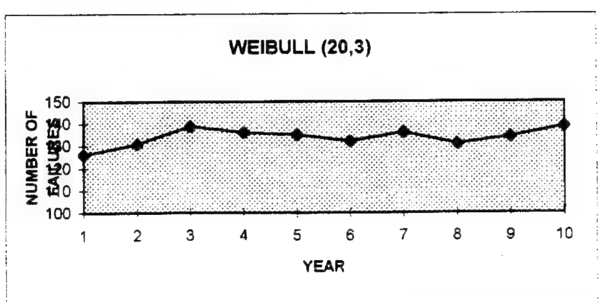
Year	Frequency
1	124
2	127
3	140
4	133
5	139
6	124
7	144
8	131
9	132
10	137
More	0



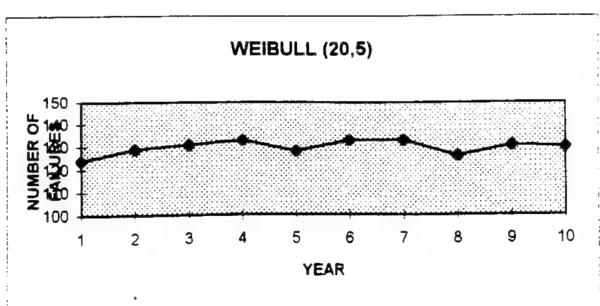
Year	Frequency
1	128
2	130
3	141
4	135
5	141
6	130
7	138
8	131
9	135
10	144
More	0



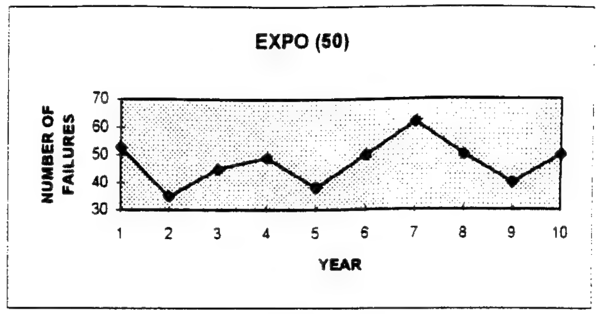
Year	Frequency
1	126
2	131
3	139
4	136
5	135
6	132
7	136
8	131
9	134
10	139
More	0



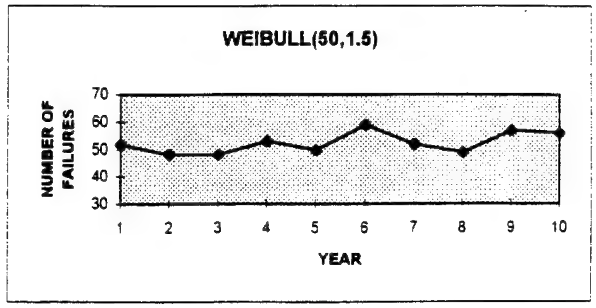
Year	Frequency
1	124
2	129
3	131
4	133
5	128
6	133
7	133
8	126
9	131
10	130
More	0



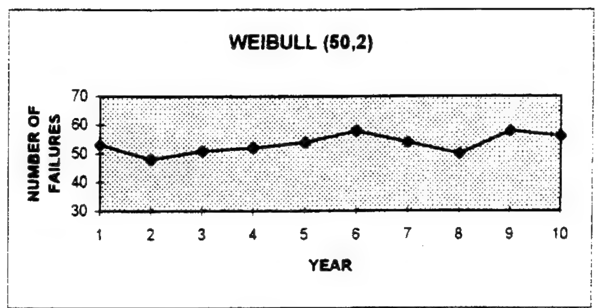
Year	Frequency
1	53
2	35
3	45
4	49
5	38
6	50
7	62
8	50
9	40
10	50
More	0



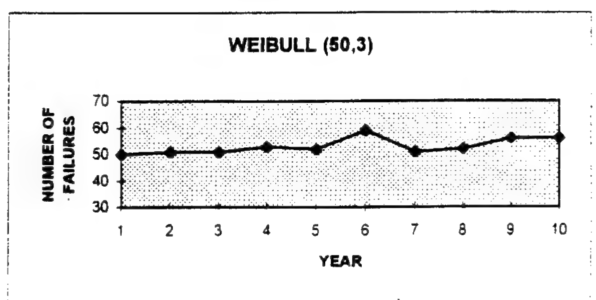
Year	Frequency
1	52
2	48
3	48
4	53
5	50
6	59
7	52
8	49
9	57
10	56
More	0



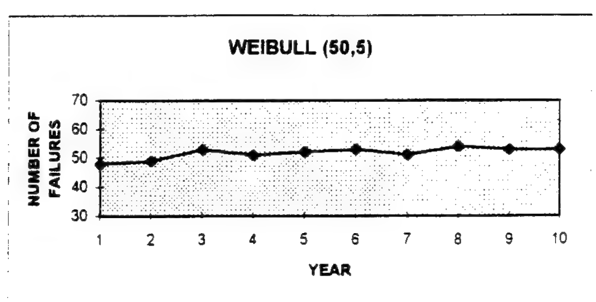
Year	Frequency
1	53
2	48
3	51
4	52
5	54
6	58
7	54
8	50
9	58
10	56
More	0



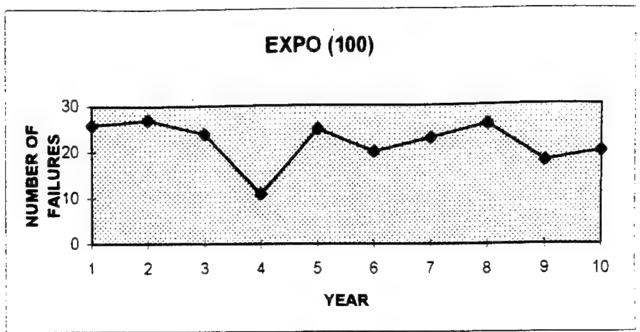
Year	Frequency
1	50
2	51
3	51
4	53
5	52
6	59
7	51
8	52
9	56
10	56
More	0



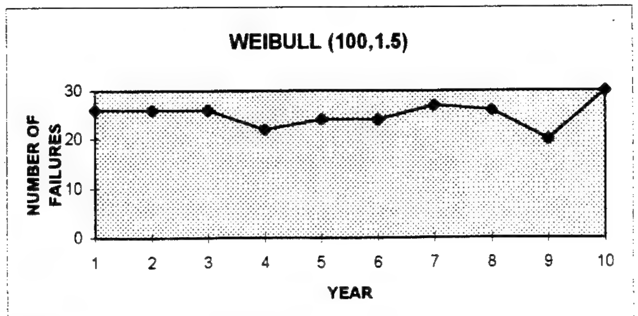
Year	Frequency
1	48
2	49
3	53
4	51
5	52
6	53
7	51
8	54
9	53
10	53
More	0



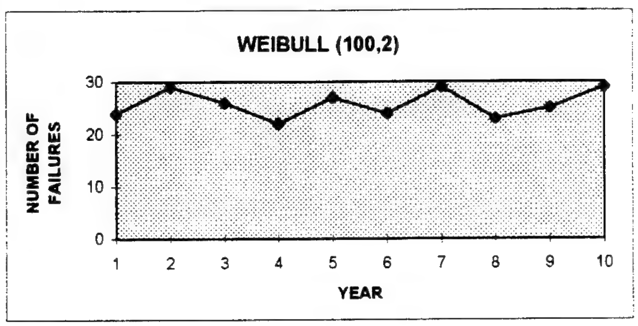
Year	Frequency
1	26
2	27
3	24
4	11
5	25
6	20
7	23
8	26
9	18
10	20
More	0



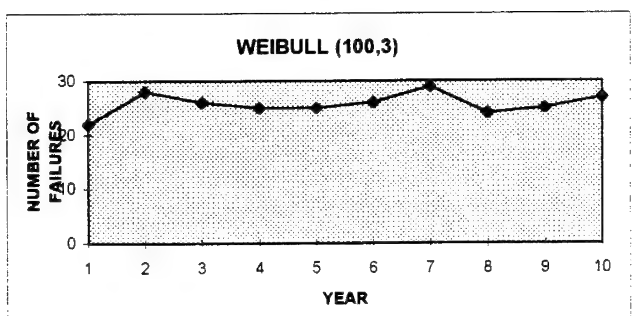
Year	Frequency
1	26
2	26
3	26
4	22
5	24
6	24
7	27
8	26
9	20
10	30
More	0



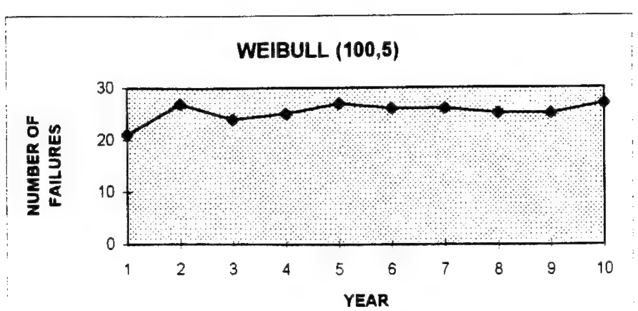
Year	Frequency
1	24
2	29
3	26
4	22
5	27
6	24
7	29
8	23
9	25
10	29
More	0



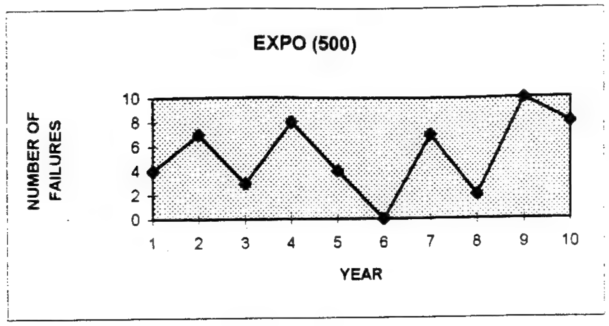
Year	Frequency
1	22
2	28
3	26
4	25
5	25
6	26
7	29
8	24
9	25
10	27
More	0



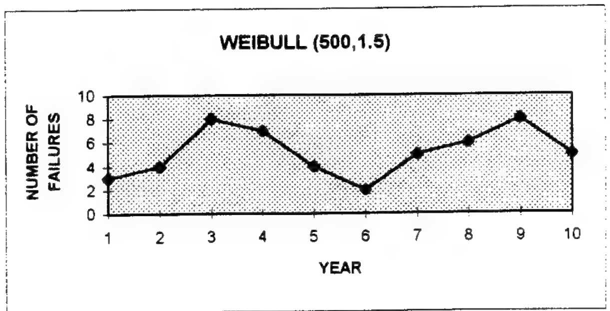
Year	Frequency
1	21
2	27
3	24
4	25
5	27
6	26
7	26
8	25
9	25
10	27
More	0



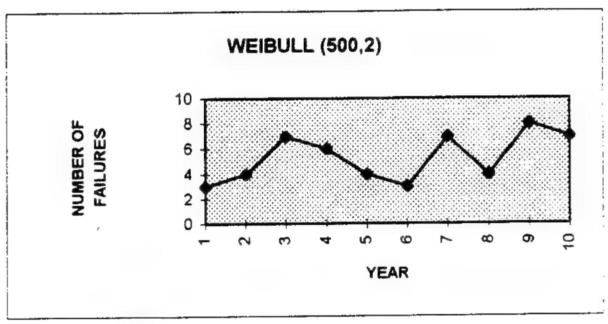
Year	Frequency
1	4
2	7
3	3
4	8
5	4
6	0
7	7
8	2
9	10
10	8
More	0



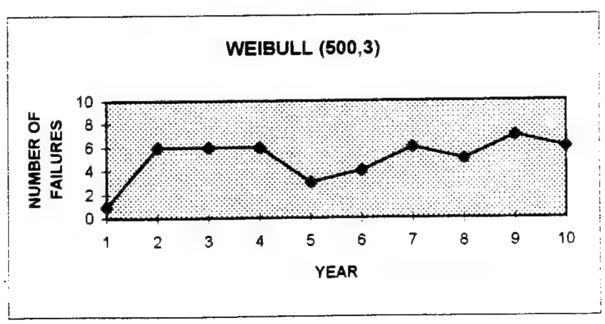
Year	Frequency
1	3
2	4
3	8
4	7
5	4
6	2
7	5
8	6
9	8
10	5
More	0



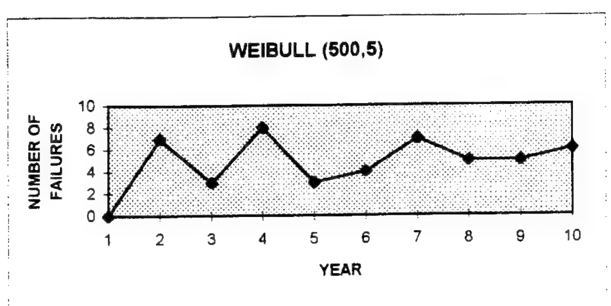
Year	Frequency
1	3
2	4
3	7
4	6
5	4
6	3
7	7
8	4
9	8
10	7
More	0



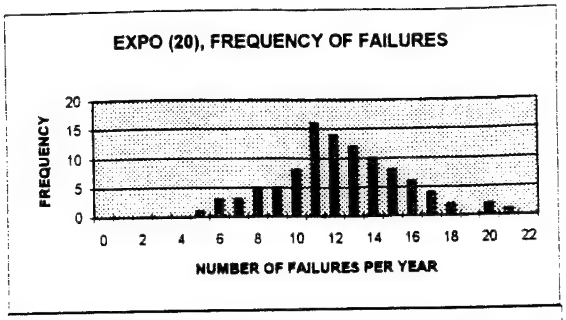
Year	Frequency
1	1
2	6
3	6
4	6
5	3
6	4
7	6
8	5
9	7
10	6
More	0

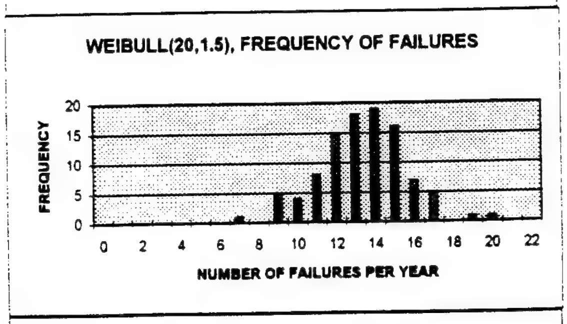


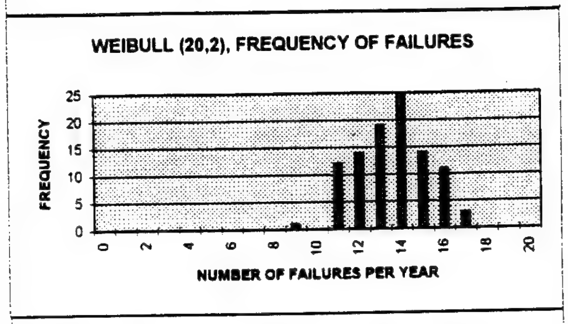
Year	Frequency
1	0
2	7
3	3
4	8
5	3
6	4
7	7
8	5
9	5
10	6
More	0

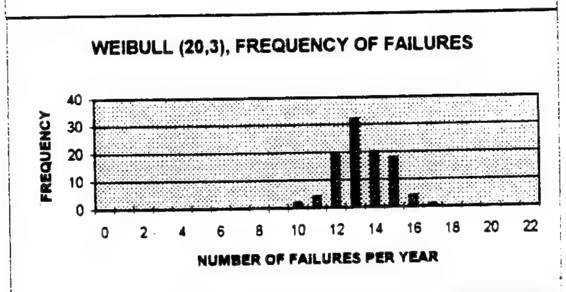


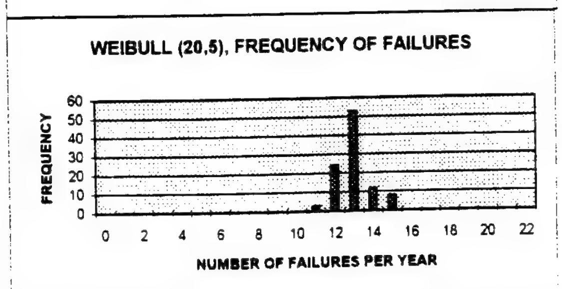
APPENDIX H:
FREQUENCY OF FAILURE GRAPHS

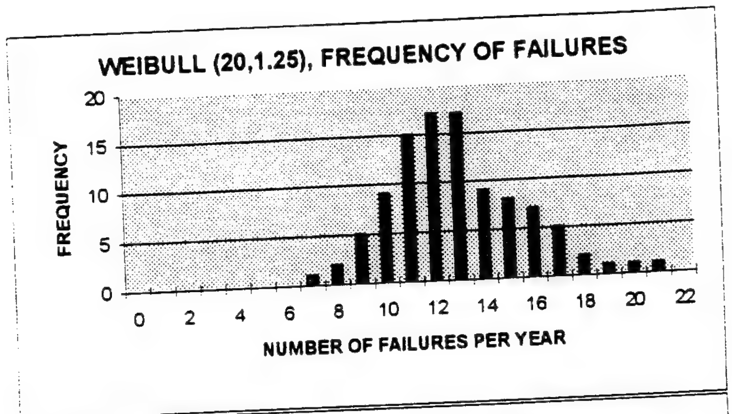


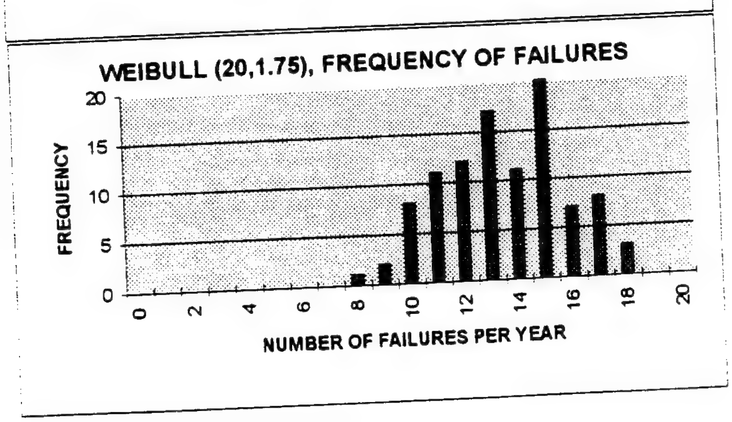


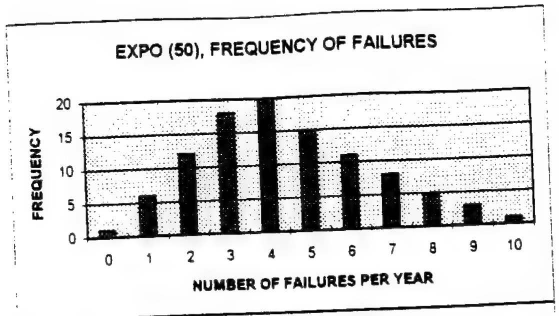


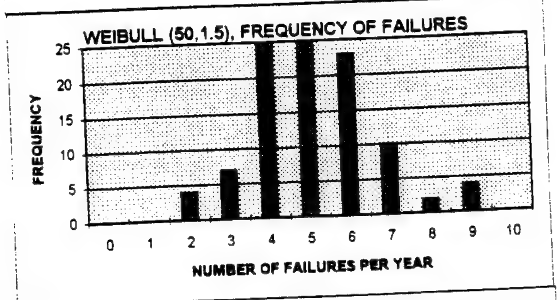


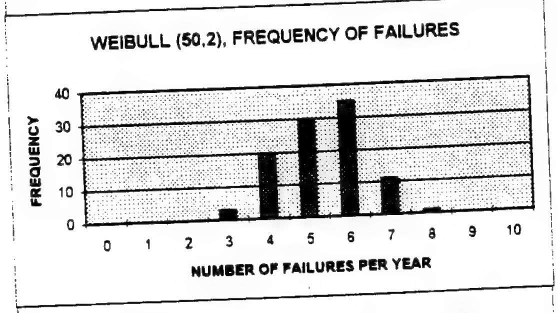


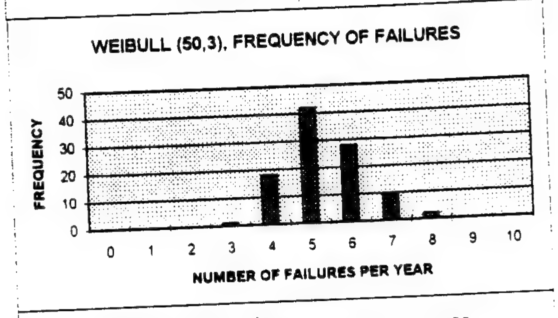

WEIBULL (20,1.25), FREQUENCY OF FAILURES
FREQUENCY
NUMBER OF FAILURES PER YEAR
0
5
10
15
20
0
2
4
6
8
10
12
14
16
18
20
22

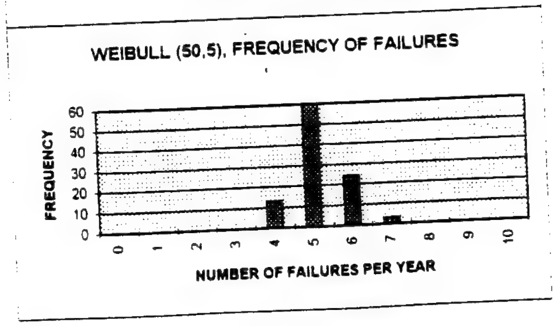

WEIBULL (20,1.75), FREQUENCY OF FAILURES
FREQUENCY
NUMBER OF FAILURES PER YEAR
0
5
10
15
20
0
2
4
6
8
10
12
14
16
18
20

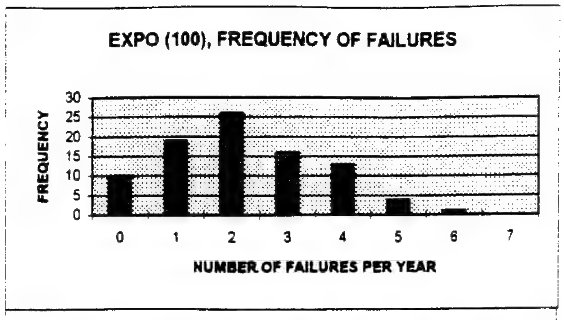

EXPO (50), FREQUENCY OF FAILURES
FREQUENCY
0 5 10 15 20
0 1 2 3 4 5 6 7 8 9 10
NUMBER OF FAILURES PER YEAR

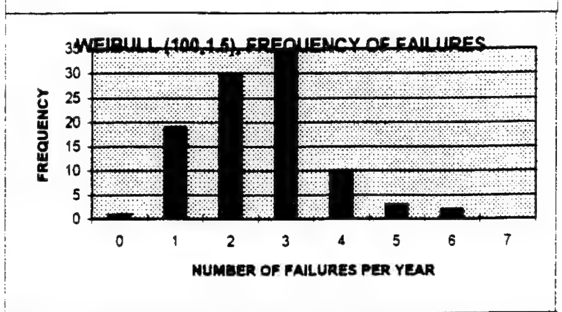

WEIBULL (50,1.5), FREQUENCY OF FAILURES
FREQUENCY
0 5 10 15 20 25
0 1 2 3 4 5 6 7 8 9 10
NUMBER OF FAILURES PER YEAR

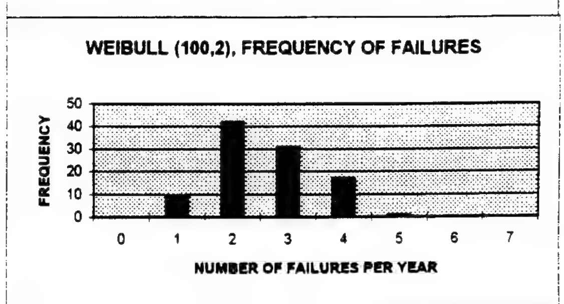

WEIBULL (50,2), FREQUENCY OF FAILURES
FREQUENCY
0 10 20 30 40
0 1 2 3 4 5 6 7 8 9 10
NUMBER OF FAILURES PER YEAR

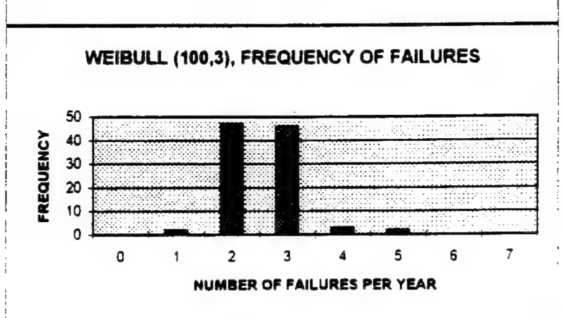

WEIBULL (50,3), FREQUENCY OF FAILURES
FREQUENCY
0 10 20 30 40 50
0 1 2 3 4 5 6 7 8 9 10
NUMBER OF FAILURES PER YEAR

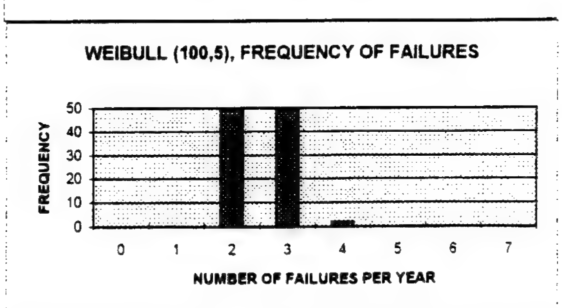

WEIBULL (50,5), FREQUENCY OF FAILURES
FREQUENCY
0 10 20 30 40 50 60
0 1 2 3 4 5 6 7 8 9 10
NUMBER OF FAILURES PER YEAR

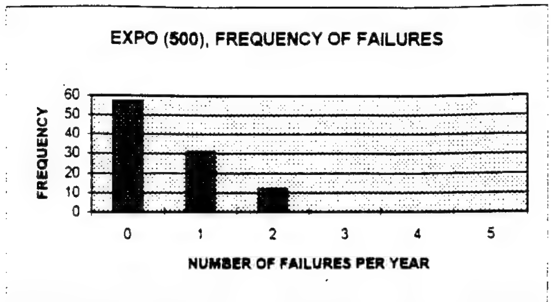

EXPO (100), FREQUENCY OF FAILURES
FREQUENCY
0 5 10 15 20 25 30
0 1 2 3 4 5 6 7
NUMBER OF FAILURES PER YEAR

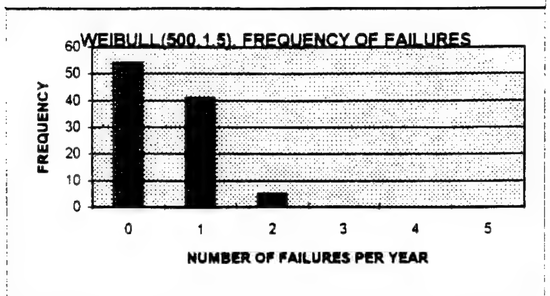

WEIBULL (100,1.5), FREQUENCY OF FAILURES
FREQUENCY
0 5 10 15 20 25 30 35
0 1 2 3 4 5 6 7
NUMBER OF FAILURES PER YEAR

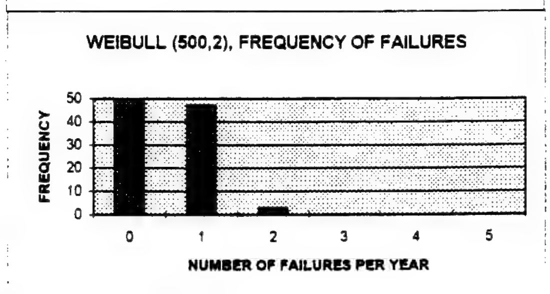

WEIBULL (100,2), FREQUENCY OF FAILURES
FREQUENCY
0 10 20 30 40 50
0 1 2 3 4 5 6 7
NUMBER OF FAILURES PER YEAR

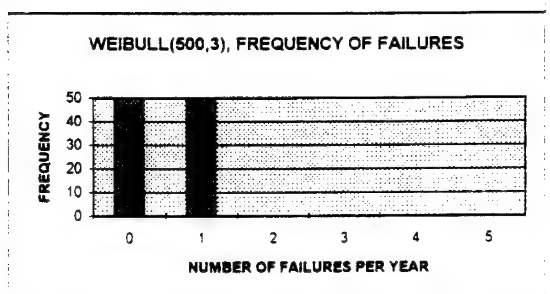

WEIBULL (100,3), FREQUENCY OF FAILURES
FREQUENCY
0 10 20 30 40 50
0 1 2 3 4 5 6 7
NUMBER OF FAILURES PER YEAR

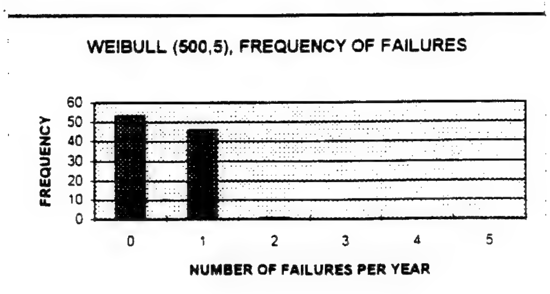

WEIBULL (100,5), FREQUENCY OF FAILURES
FREQUENCY
0 10 20 30 40 50
0 1 2 3 4 5 6 7
NUMBER OF FAILURES PER YEAR


EXPO (500), FREQUENCY OF FAILURES
FREQUENCY
60
50
40
30
20
10
0
0
1
2
3
4
5
NUMBER OF FAILURES PER YEAR


WEIBULL(500,1.5), FREQUENCY OF FAILURES
FREQUENCY
60
50
40
30
20
10
0
0
1
2
3
4
5
NUMBER OF FAILURES PER YEAR


WEIBULL (500,2), FREQUENCY OF FAILURES
FREQUENCY
50
40
30
20
10
0
0
1
2
3
4
5
NUMBER OF FAILURES PER YEAR


WEIBULL(500,3), FREQUENCY OF FAILURES
FREQUENCY
50
40
30
20
10
0
0
1
2
3
4
5
NUMBER OF FAILURES PER YEAR


WEIBULL (500,5), FREQUENCY OF FAILURES
FREQUENCY
60
50
40
30
20
10
0
0
1
2
3
4
5
NUMBER OF FAILURES PER YEAR

APPENDIX I: FINANCIAL SPREADSHEET OUTPUT

This appendix contains examples of the output from the financial spreadsheet used to determine potential cost savings. The author has chosen to include only those with a comparison to the mean or eta value of 20 hours. The output from these spreadsheets is fully explained in Chapter V.

NET PRESENT VALUE CALCULATIONS

CURRENT ASSUMPTION = EXPO (20)
PROPOSED ASSUMPTION = EXPO (50)

INTEREST RATE =	10%
FLIGHT HRS/YR =	240
COST OF MOD =	$ 1,000.00
LABOR COST =	$ 25.00
CUR FAILRATE =	0.050
PRO FAILRATE =	0.020
LABOR HOURS =	10
CURFAIL/YR =	12.07
PRO FAIL/YR=	4.72

TOTAL SAVINGS = $ 771,860.67

YEAR	ENG INTRODUCED	ATTRITION	TOTAL IN SERVICE	TOT FLY HRS	CUR EXP FAIL	PRO EXP FAIL	CUR COST	PRO COST	PRO SAVINGS	NPV PRO SAV
1	10	0	10	2400	120.7	47.2	$ 30,175.00	$ 21,800.00	$ 8,375.00	$ 8,375.00
2	10	0	20	4800	241.4	94.4	$ 60,350.00	$ 33,600.00	$ 26,750.00	$ 32,693.18
3	10	0	30	7200	362.1	141.6	$ 90,525.00	$ 45,400.00	$ 45,125.00	$ 69,986.57
4	10	0	40	9600	482.8	188.8	$ 120,700.00	$ 57,200.00	$ 63,500.00	$ 117,695.06
5	10	0	50	12000	603.5	236	$ 150,875.00	$ 69,000.00	$ 81,875.00	$ 173,616.79
6	10	0	60	14400	724.2	283.2	$ 181,050.00	$ 80,800.00	$ 100,250.00	$ 235,864.15
7	10	0	70	16800	844.9	330.4	$ 211,225.00	$ 92,600.00	$ 118,625.00	$ 302,824.87
8	10	0	80	19200	965.6	377.6	$ 241,400.00	$ 104,400.00	$ 137,000.00	$ 373,127.53
9	10	0	90	21600	1086.3	424.8	$ 271,575.00	$ 116,200.00	$ 155,375.00	$ 445,611.12
10	10	0	100	24000	1207	472	$ 301,750.00	$ 128,000.00	$ 173,750.00	$ 519,298.08
11	0	10	90	21600	1086.3	424.8	$ 271,575.00	$ 106,200.00	$ 165,375.00	$ 583,057.30
12	0	10	80	19200	965.6	377.6	$ 241,400.00	$ 94,400.00	$ 147,000.00	$ 634,579.90
13	0	10	70	16800	844.9	330.4	$ 211,225.00	$ 82,600.00	$ 128,625.00	$ 675,563.79
14	0	10	60	14400	724.2	283.2	$ 181,050.00	$ 70,800.00	$ 110,250.00	$ 707,499.29
15	0	10	50	12000	603.5	236	$ 150,875.00	$ 59,000.00	$ 91,875.00	$ 731,692.85
16	0	10	40	9600	482.8	188.8	$ 120,700.00	$ 47,200.00	$ 73,500.00	$ 749,288.16
17	0	10	30	7200	362.1	141.6	$ 90,525.00	$ 35,400.00	$ 55,125.00	$ 761,284.97
18	0	10	20	4800	241.4	94.4	$ 60,350.00	$ 23,600.00	$ 36,750.00	$ 768,555.76
19	0	10	10	2400	120.7	47.2	$ 30,175.00	$ 11,800.00	$ 18,375.00	$ 771,860.67
20	0	10	0	0	0	0	$ -	$ -	$ -	$ 771,860.67
TOTALS							$ 3,017,500.00	$ 1,280,000.00	$ 1,737,500.00	$ 771,860.67

NET PRESENT VALUE CALCULATIONS

CURRENT ASSUMPTION = WEIB(20,1.5)
PROPOSED ASSUMPTION = WEIB (50,1.5)

INTEREST RATE =	10%
FLIGHT HRS/YR =	240
COST OF MOD =	$ 1,000.00
LABOR COST =	$ 25.00
CUR FAILRATE =	0.055
PRO FAILRATE =	0.022
LABOR HOURS =	10
CURFAIL/YR =	13.31
PRO FAIL/YR=	5.24

TOTAL SAVINGS = $ 854,092.59

YEAR	ENG INTRODUCED	ATTRITION	TOTAL IN SERVICE	TOT FLY HRS	CUR EXP FAIL	PRO EXP FAIL	CUR COST	PRO COST	PRO SAVINGS	NPV PRO SAV
1	10	0	10	2400	133.1	52.4	$ 33,275.00	$ 23,100.00	$ 10,175.00	$ 10,175.00
2	10	0	20	4800	266.2	104.8	$ 66,550.00	$ 36,200.00	$ 30,350.00	$ 37,765.91
3	10	0	30	7200	399.3	157.2	$ 99,825.00	$ 49,300.00	$ 50,525.00	$ 79,522.11
4	10	0	40	9600	532.4	209.6	$ 133,100.00	$ 62,400.00	$ 70,700.00	$ 132,640.06
5	10	0	50	12000	665.5	262	$ 166,375.00	$ 75,500.00	$ 90,875.00	$ 194,708.91
6	10	0	60	14400	798.6	314.4	$ 199,650.00	$ 88,600.00	$ 111,050.00	$ 263,662.22
7	10	0	70	16800	931.7	366.8	$ 232,925.00	$ 101,700.00	$ 131,225.00	$ 337,735.32
8	10	0	80	19200	1064.8	419.2	$ 266,200.00	$ 114,800.00	$ 151,400.00	$ 415,427.46
9	10	0	90	21600	1197.9	471.6	$ 299,475.00	$ 127,900.00	$ 171,575.00	$ 495,468.46
10	10	0	100	24000	1331	524	$ 332,750.00	$ 141,000.00	$ 191,750.00	$ 576,789.18
11	0	10	90	21600	1197.9	471.6	$ 299,475.00	$ 117,900.00	$ 181,575.00	$ 646,794.20
12	0	10	80	19200	1064.8	419.2	$ 266,200.00	$ 104,800.00	$ 161,400.00	$ 703,363.92
13	0	10	70	16800	931.7	366.8	$ 232,925.00	$ 91,700.00	$ 141,225.00	$ 748,362.55
14	0	10	60	14400	798.6	314.4	$ 199,650.00	$ 78,600.00	$ 121,050.00	$ 783,426.43
15	0	10	50	12000	665.5	262	$ 166,375.00	$ 65,500.00	$ 100,875.00	$ 809,989.97
16	0	10	40	9600	532.4	209.6	$ 133,100.00	$ 52,400.00	$ 80,700.00	$ 829,308.90
17	0	10	30	7200	399.3	157.2	$ 99,825.00	$ 39,300.00	$ 60,525.00	$ 842,480.91
18	0	10	20	4800	266.2	104.8	$ 66,550.00	$ 26,200.00	$ 40,350.00	$ 850,463.94
19	0	10	10	2400	133.1	52.4	$ 33,275.00	$ 13,100.00	$ 20,175.00	$ 854,092.59
20	0	10	0	0	0	0	$ -	$ -	$ -	$ 854,092.59
TOTALS							$ 3,327,500.00	$ 1,410,000.00	$ 1,917,500.00	$ 854,092.59

NET PRESENT VALUE CALCULATIONS

CURRENT ASSUMPTION = WEIB(20,2)
PROPOSED ASSUMPTION = WEIB (50,2)

INTEREST RATE =	10%
FLIGHT HRS/YR =	240
COST OF MOD =	$ 1,000.00
LABOR COST =	$ 25.00
CUR FAILRATE =	0.056
PRO FAILRATE =	0.022
LABOR HOURS =	10
CURFAIL/YR =	13.53
PRO FAIL/YR=	5.34

TOTAL SAVINGS = $ 867,797.91

YEAR	ENG INTRODUCED	ATTRITION	TOTAL IN SERVICE	TOT FLY HRS	CUR EXP FAIL	PRO EXP FAIL	CUR COST	PRO COST	PRO SAVINGS	NPV PRO SAV
1	10	0	10	2400	135.3	53.4	$ 33,825.00	$ 23,350.00	$ 10,475.00	$ 10,475.00
2	10	0	20	4800	270.6	106.8	$ 67,650.00	$ 36,700.00	$ 30,950.00	$ 38,611.36
3	10	0	30	7200	405.9	160.2	$ 101,475.00	$ 50,050.00	$ 51,425.00	$ 81,111.36
4	10	0	40	9600	541.2	213.6	$ 135,300.00	$ 63,400.00	$ 71,900.00	$ 135,130.90
5	10	0	50	12000	676.5	267	$ 169,125.00	$ 76,750.00	$ 92,375.00	$ 198,224.27
6	10	0	60	14400	811.8	320.4	$ 202,950.00	$ 90,100.00	$ 112,850.00	$ 268,295.24
7	10	0	70	16800	947.1	373.8	$ 236,775.00	$ 103,450.00	$ 133,325.00	$ 343,553.72
8	10	0	80	19200	1082.4	427.2	$ 270,600.00	$ 116,800.00	$ 153,800.00	$ 422,477.44
9	10	0	90	21600	1217.7	480.6	$ 304,425.00	$ 130,150.00	$ 174,275.00	$ 503,778.02
10	10	0	100	24000	1353	534	$ 338,250.00	$ 143,500.00	$ 194,750.00	$ 586,371.03
11	0	10	90	21600	1217.7	480.6	$ 304,425.00	$ 120,150.00	$ 184,275.00	$ 657,417.02
12	0	10	80	19200	1082.4	427.2	$ 270,600.00	$ 106,800.00	$ 163,800.00	$ 714,827.92
13	0	10	70	16800	947.1	373.8	$ 236,775.00	$ 93,450.00	$ 143,325.00	$ 760,495.68
14	0	10	60	14400	811.8	320.4	$ 202,950.00	$ 80,100.00	$ 122,850.00	$ 796,080.95
15	0	10	50	12000	676.5	267	$ 169,125.00	$ 66,750.00	$ 102,375.00	$ 823,039.49
16	0	10	40	9600	541.2	213.6	$ 135,300.00	$ 53,400.00	$ 81,900.00	$ 842,645.69
17	0	10	30	7200	405.9	160.2	$ 101,475.00	$ 40,050.00	$ 61,425.00	$ 856,013.56
18	0	10	20	4800	270.6	106.8	$ 67,650.00	$ 26,700.00	$ 40,950.00	$ 864,115.30
19	0	10	10	2400	135.3	53.4	$ 33,825.00	$ 13,350.00	$ 20,475.00	$ 867,797.91
20	0	10	0	0	0	0	$ -	$ -	$ -	$ 867,797.91
TOTALS							$ 3,382,500.00	$ 1,435,000.00	$ 1,947,500.00	$ 867,797.91

NET PRESENT VALUE CALCULATIONS

CURRENT ASSUMPTION = WEIB(20,3)
PROPOSED ASSUMPTION = WEIB (50,3)

INTEREST RATE =	10%
FLIGHT HRS/YR =	240
COST OF MOD =	$ 1,000 00
LABOR COST =	$ 25 00
CUR FAILRATE =	0 056
PRO FAILRATE =	0 022
LABOR HOURS =	10
CURFAIL/YR =	13 39
PRO FAIL/YR=	5 32

TOTAL SAVINGS = $ 854,092 59

YEAR	ENG INTRODUCED	ATTRITION	TOTAL IN SERVICE	TOT FLY HRS	CUR EXP FAIL	PRO EXP FAIL	CUR COST	PRO COST	PRO SAVINGS	NPV PRO SAV
1	10	0	10	2400	133 9	53 2	$ 33,475 00	$ 23,300 00	$ 10,175 00	$ 10,175 00
2	10	0	20	4800	267 8	106 4	$ 66,950 00	$ 36,600 00	$ 30,350 00	$ 37,765 91
3	10	0	30	7200	401 7	159 6	$ 100,425 00	$ 49,900 00	$ 50,525 00	$ 79,522 11
4	10	0	40	9600	535 6	212 8	$ 133,900 00	$ 63,200 00	$ 70,700 00	$ 132,640 06
5	10	0	50	12000	669 5	266	$ 167,375 00	$ 76,500 00	$ 90,875 00	$ 194,708 91
6	10	0	60	14400	803 4	319 2	$ 200,850 00	$ 89,800 00	$ 111,050 00	$ 263,662 22
7	10	0	70	16800	937 3	372 4	$ 234,325 00	$ 103,100 00	$ 131,225 00	$ 337,735 32
8	10	0	80	19200	1071 2	425 6	$ 267,800 00	$ 116,400 00	$ 151,400 00	$ 415,427 46
9	10	0	90	21600	1205 1	478 8	$ 301,275 00	$ 129,700 00	$ 171,575 00	$ 495,468 46
10	10	0	100	24000	1339	532	$ 334,750 00	$ 143,000 00	$ 191,750 00	$ 576,789 18
11	0	10	90	21600	1205 1	478 8	$ 301,275 00	$ 119,700 00	$ 181,575 00	$ 646,794 20
12	0	10	80	19200	1071 2	425 6	$ 267,800 00	$ 106,400 00	$ 161,400 00	$ 703,363 92
13	0	10	70	16800	937 3	372 4	$ 234,325 00	$ 93,100 00	$ 141,225 00	$ 748,362 55
14	0	10	60	14400	803 4	319 2	$ 200,850 00	$ 79,800 00	$ 121,050 00	$ 783,426 43
15	0	10	50	12000	669 5	266	$ 167,375 00	$ 66,500 00	$ 100,875 00	$ 809,989 97
16	0	10	40	9600	535 6	212 8	$ 133,900 00	$ 53,200 00	$ 80,700 00	$ 829,308 90
17	0	10	30	7200	401 7	159 6	$ 100,425 00	$ 39,900 00	$ 60,525 00	$ 842,480 91
18	0	10	20	4800	267 8	106 4	$ 66,950 00	$ 26,600 00	$ 40,350 00	$ 850,463 94
19	0	10	10	2400	133 9	53 2	$ 33,475 00	$ 13,300 00	$ 20,175 00	$ 854,092 59
20	0	10	0	0	0	0	$ -	$ -	$ -	$ 854,092 59
TOTALS							$ 3,347,500 00	$ 1,430,000 00	$ 1,917,500 00	$ 854,092 59

NET PRESENT VALUE CALCULATIONS

CURRENT ASSUMPTION = WEIB(20,5)
PROPOSED ASSUMPTION = WEIB (50,5)

INTEREST RATE =	10%
FLIGHT HRS/YR =	240
COST OF MOD =	$ 1,000.00
LABOR COST =	$ 25.00
CUR FAILRATE =	0.054
PRO FAILRATE =	0.022
LABOR HOURS =	10
CURFAIL/YR =	12.98
PRO FAIL/YR=	5.17

TOTAL SAVINGS = $ 824,397.73

YEAR	ENG INTRODUCED	ATTRITION	TOTAL IN SERVICE	TOT FLY HRS	CUR EXP FAIL	PRO EXP FAIL	CUR COST	PRO COST	PRO SAVINGS	NPV PRO SAV
1	10	0	10	2400	129.8	51.7	$ 32,450.00	$ 22,925.00	$ 9,525.00	$ 9,525.00
2	10	0	20	4800	259.6	103.4	$ 64,900.00	$ 35,850.00	$ 29,050.00	$ 35,934.09
3	10	0	30	7200	389.4	155.1	$ 97,350.00	$ 48,775.00	$ 48,575.00	$ 76,078.72
4	10	0	40	9600	519.2	206.8	$ 129,800.00	$ 61,700.00	$ 68,100.00	$ 127,243.26
5	10	0	50	12000	649	258.5	$ 162,250.00	$ 74,625.00	$ 87,625.00	$ 187,092.31
6	10	0	60	14400	778.8	310.2	$ 194,700.00	$ 87,550.00	$ 107,150.00	$ 253,624.03
7	10	0	70	16800	908.6	361.9	$ 227,150.00	$ 100,475.00	$ 126,675.00	$ 325,128.77
8	10	0	80	19200	1038.4	413.6	$ 259,600.00	$ 113,400.00	$ 146,200.00	$ 400,152.48
9	10	0	90	21600	1168.2	465.3	$ 292,050.00	$ 126,325.00	$ 165,725.00	$ 477,464.42
10	10	0	100	24000	1298	517	$ 324,500.00	$ 139,250.00	$ 185,250.00	$ 556,028.50
11	0	10	90	21600	1168.2	465.3	$ 292,050.00	$ 116,325.00	$ 175,725.00	$ 623,778.10
12	0	10	80	19200	1038.4	413.6	$ 259,600.00	$ 103,400.00	$ 156,200.00	$ 678,525.24
13	0	10	70	16800	908.6	361.9	$ 227,150.00	$ 90,475.00	$ 136,675.00	$ 722,074.11
14	0	10	60	14400	778.8	310.2	$ 194,700.00	$ 77,550.00	$ 117,150.00	$ 756,008.29
15	0	10	50	12000	649	258.5	$ 162,250.00	$ 64,625.00	$ 97,625.00	$ 781,716.01
16	0	10	40	9600	519.2	206.8	$ 129,800.00	$ 51,700.00	$ 78,100.00	$ 800,412.53
17	0	10	30	7200	389.4	155.1	$ 97,350.00	$ 38,775.00	$ 58,575.00	$ 813,160.15
18	0	10	20	4800	259.6	103.4	$ 64,900.00	$ 25,850.00	$ 39,050.00	$ 820,885.99
19	0	10	10	2400	129.8	51.7	$ 32,450.00	$ 12,925.00	$ 19,525.00	$ 824,397.73
20	0	10	0	0	0	0	$ -	$ -	$ -	$ 824,397.73
TOTALS							$ 3,245,000.00	$ 1,392,500.00	$ 1,852,500.00	$ 824,397.73

LIST OF REFERENCES

1. Reeves, R.R., "A User's guide for the Cost Effectiveness Analysis Spreadsheet Model for Aircraft Engines (CEAMOD Version 2.0)," M.S. Thesis, Naval Postgraduate School, Monterey, CA 93943, 1993.

2. Crowder, G.L., "Evaluation of the Cost Effectiveness Analysis Model for the Component Improvement Programs of the Air force and Navy," M.S. Thesis, Naval Postgraduate School, Monterey, CA 93943, 1992.

3. Hager, C. F., "Applications of the Weibull Distribution," M.S. Thesis, Naval Postgraduate School, Monterey, CA, 93943, 1963.

4. Rau, K. F., "An Analysis of Non-Integerizing the Aircraft Engines Cost Effectiveness Spreadsheet Model (CEAMOD 2.0)," M.S. Thesis, Naval Postgraduate School, Monterey CA 93943, 1993.

5. Abernathy, R. B., Breneman, J.E., Medlin, C.H.and Reinman, G.L., "Weibull Analysis Handbook," Rpt. No. AFWAL-TR-83-2079, Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, 1983.

6. Blanchard, B.S., *Logistics Engineering and Management*; Fourth Edition, Prentice Hall, Englewood Cliffs, NJ; 1992.

7. Pegden, C.D., Shannon, R.E. and Sadowski, R.P., *Introduction to Simulation Using SIMAN*; McGraw Hill, Hightstown, NJ; 1990.

8. Miller, I., and Freund, J.E., *Probability and Statistics for Engineers*; Second Edition, Prentice Hall, Englewood Cliffs, NJ; 1977.

9. McMasters, A.W., CEA User's Group Meeting Minutes from Meeting Held April 1992.

10. Martens, S.L., "Estimating Characteristic Life and Reliability of an Aircraft Engine Component Improvement in the Early Stages of the Implementation Process," M.S. Thesis, Naval Postgraduate School, Monterey, CA 93943, 1992.

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